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Monitoring Groundwater Quality
The Impact of In-situ Oil Shale Retorting

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16. ABSTRACT

This report presents the initial phase of a research program which will develop a planning methodology for the design and implementation of cost-effective groundwater quality monitoring programs for modified in-situ (MIS) oil shale retorting. This initial phase includes (1) a review of MIS development with regard to potential impacts and a review of current MIS monitoring programs, and (2) identification of key issues, uncertainties, and unknowns with regard to design and implementation of monitoring programs.

In addition, this report presents a preliminary study program for Phase II of the research effort. Phase II will develop support data to finalize recommendations for monitoring the impact of MIS retorts.

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Groundwater	Water Pollution Sources	08H
In-Situ Oil Shale Retorting	Monitoring Methodology	08I
Oil Shale	Pollutant Identification	13B
Mine Wastes	Pollutant Source	
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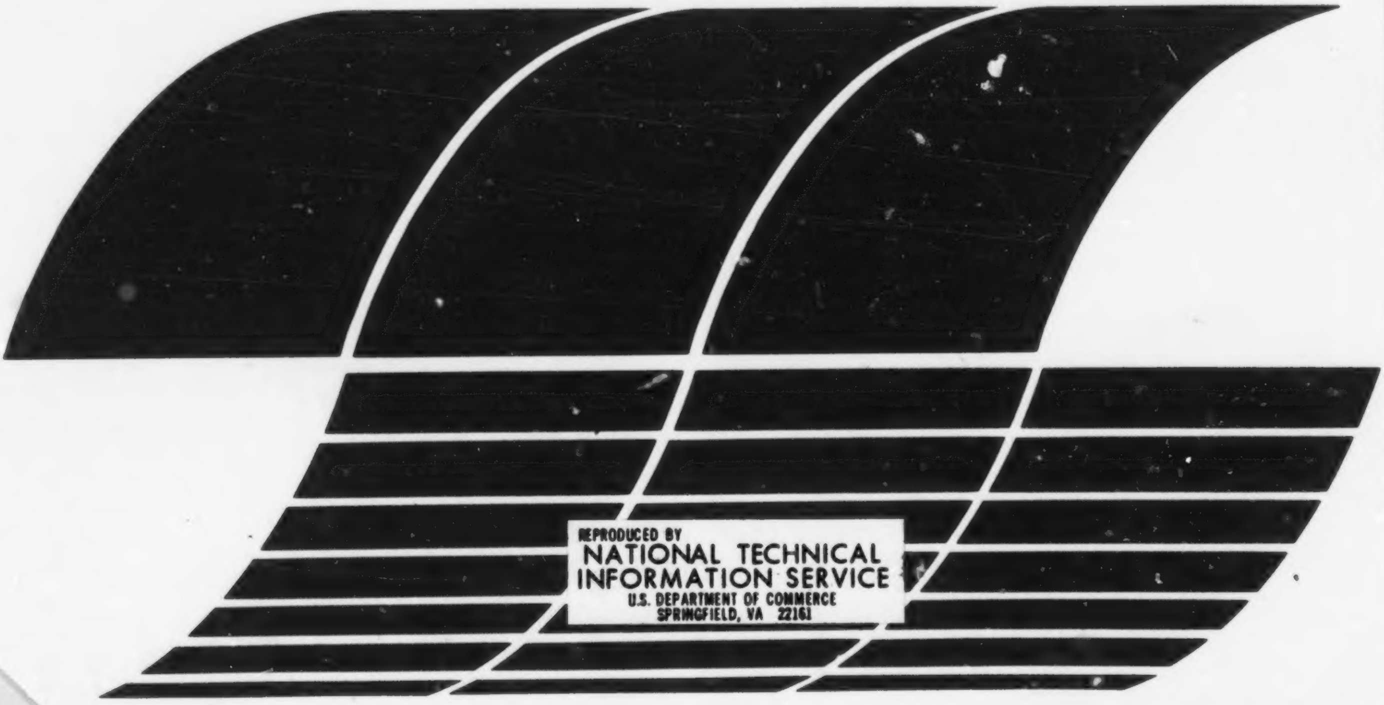

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MONITORING GROUNDWATER QUALITY:

The Impact of In Situ Oil Shale Retorting

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FOREWORD

Protection of the environment requires effective regulatory actions based on sound technical and scientific data. The data must include the quantitative description and linking of pollutant sources, transport mechanisms, interactions, and resulting effects on man and his environment. Because of the complexities involved, assessment of exposure to specific pollutants in the environment requires a total systems approach that transcends the media of air, water, and land. The Environmental Monitoring Systems Laboratory at Las Vegas contributes to the formation and enhancement of a sound monitoring-data base for exposure assessment through programs designed to:

- Develop and optimize systems and strategies for monitoring pollutants and their impact on the environment
- Demonstrate new monitoring systems and technologies by applying them to fulfill special monitoring needs of the Agency's operating programs.

This report presents the initial phases of a study of design and implementation of groundwater quality monitoring programs for modified in-situ (MIS) oil shale retorting in the Western United States. The development of preliminary priority ranking of potential pollution sources and the pollutants associated with these sources is presented. Currently proposed MIS monitoring programs are reviewed. Key issues and uncertainties with regard to groundwater quality impacts and monitoring are identified.

The results of this report are the initial segment of a design and testing program. Further testing and evaluation in the following program segment (Phase II) will be utilized to develop recommendations for the cost-effective monitoring of MIS retorts. This study has considered the type of MIS operation proposed for Federal Prototype Lease Tracts C-a and C-b in western Colorado. These proposed developments form the case study evaluations included for this report, although the specific design of monitoring programs for these development tracts is not the purpose of this research project.

The research program, of which this report is part, is intended to provide technical information and a planning format for the design of groundwater quality monitoring programs for this type of oil shale development. The study results may be used by industrial developers and their consultants, as well as by the various local, State, and Federal agencies with responsibilities in environmental monitoring and planning.

Further information on this study and on the subject of groundwater quality monitoring in general can be obtained by contacting the Environmental Monitoring Systems Laboratory, U.S. Environmental Protection Agency, Las Vegas, Nevada.

Glenn E. Schweitzer
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PREFACE

General Electric--TEMPO, Center for Advanced Studies, is conducting a 3-year program dealing with the design of groundwater quality monitoring programs for western oil shale. The type of oil shale development being evaluated in this study is MIS retorting as presently proposed for Federal Prototype Lease Tracts C-a and C-b in western Colorado. This study focuses specifically on the monitoring of in-situ retorts and is following a stepwise monitoring methodology developed by TEMPO.

This report represents the initial phase of this research program. The goals of this initial phase were to:

- Review MIS development with regard to potential impacts on groundwater quality and review current MIS monitoring programs
- Use this review to identify the key issues, uncertainties, and unknowns with regard to design and implementation of groundwater quality monitoring programs for MIS retorts.

These items are addressed in this report and provide a basis for Phase II studies to further investigate and evaluate these points of concern.

The goal of Phase II will be to develop support information in areas of focus defined during Phase I and to finalize recommendations for monitoring the groundwater quality impact of MIS retorts. The recommendations will provide a general evaluation and decision framework for design of monitoring programs for specific development sites. Procedures will be recommended for accomplishing the various evaluation tasks (e.g., hydrogeologic characterization and pollutant mobility assessment) and for specific monitoring activities (e.g., well construction and sample collection).

The final product of this research program will be a planning document which will provide a technical basis and a methodology for the design of groundwater quality monitoring programs for oil shale industrial developers and the various governmental agencies concerned with environmental planning and protection.

SUMMARY AND DESIGN RECOMMENDATIONS

INTRODUCTION

This report summarizes and evaluates the data compiled during Phase I of this research project. The general goals of Phase I were to:

1. Review MIS oil shale retorting with regard to potential impacts on groundwater quality and review development of currently operating or proposed MIS monitoring programs on Federal Lease Tracts C-a and C-b

2. Develop preliminary recommendations for the design and implementation of groundwater quality monitoring programs for MIS retorts.

The final goal of this research program is to develop cost-effective monitoring designs for MIS retorts. Before the issue of cost effectiveness can be addressed completely, a comprehensive analysis of the current state of development of MIS monitoring must be completed. This required analysis is presented in this report.

The Phase I review and assessment has led to the preparation of a preliminary monitoring approach for this new type of industrial development. In addition, the uncertainties and unknowns that exist with regard to evaluating and monitoring MIS retorts have been identified. Phase II of this project has been designed to address these factors and to develop data pertinent to finalizing a recommended monitoring approach. These final recommendations will be based on technical issues, such as identified in this report, and on supplemental technical and cost data developed during Phase II studies.

GENERAL MONITORING STRATEGY

The basic goals of monitoring are to (1) detect and measure groundwater flow within the abandoned retort interval and (2) to detect changes in groundwater quality from waste residuals (e.g., spent shale, retort water) within the abandoned retort zone.

Because of the nature of MIS retort development and the subsurface location of the retorts, a potential exists for contact of groundwaters with spent shale materials and subsequent leaching of soluble inorganic and organic constituents from the retort zone. The characteristics and extent of these potential impacts are highly dependent on site-specific hydrogeologic conditions (e.g., extent of fracturing, location of aquifers relative to retort interval, head relationship between aquifers, etc.). Consideration of these factors will result in groundwater quality monitoring programs which are, in detail, defined by site-specific and development-specific features. There are, however, generic monitoring design and operational procedures which are recommended for development of programs for specific sites.

The focus of this evaluation and the resulting recommendations is the MIS retorts. Thus, characterization and monitoring of deep aquifers is the topic of this summary.

It is the general conclusion of the Phase I assessment that equipment and evaluation techniques are available which can provide accurate characterization of site-specific hydrogeologic features and hence allow development of sound groundwater quality monitoring programs. Outlined below are preliminary recommendations for the design and implementation of monitoring programs. These strategies and methods are appreciably different than approaches described for the existing MIS tracts (see Section 9). General monitoring strategy recommendations are as follows:

1. Source-specific orientation. Groundwater quality monitoring networks should be designed specifically for detecting groundwater inflow to the abandoned retort zone and related effects on groundwater quality. Monitoring strategies focusing on measuring groundwater quality on a large (regional or large tract) scale cannot be expected to provide for early detection of potential pollution problems and implementation of environmental control measures. For the most part, existing hydrogeologic characterization and baseline monitoring programs have a regional-scale focus.

2. Routine monitoring of selected "indicator" constituents. This is recommended and is considered more cost effective than the extensive water quality analysis programs currently implemented. Extensive inorganic and organic analyses are indicated as a response to impacts detected by such routine monitoring, but are not needed as part of the routine monitoring program.

3. Relatively small spatial scale. This is related to items 1 and 2. Monitoring well networks should be within and directly adjacent to abandoned retort fields.

4. Iterative design process. The monitoring design process is initiated with site exploration and resource evaluation activities. Hydrogeologic data will continue to be collected during the mine and retort construction phases. These data, in addition to MIS design changes, may necessitate revision of groundwater quality monitoring designs. Wells used for baseline studies provide for initial hydrogeologic characterization, but may not be adequate for operational monitoring needs. This is particularly true where baseline programs have

a regional-scale orientation. An iterative (planning-implementation-reevalution) procedure to address monitoring needs is recommended.

A sequence of events coordinating site development and monitoring program development is shown below. Recommended approaches include maximum use of data from site development activities, phased reevaluation of the hydrogeologic system to design a testing program as well as a monitoring program, and delay of final monitoring design and implementation to closely follow retort field operation and phased abandonment. This latter approach allows maximum use of data from mine development and dewatering activities, as well as allowing maximum reponse to mine/retort design changes.

This design sequence deals with a recommended approach for work on a new oil shale tract. Specific recommendations for modification of site development and monitoring programs already underway are beyond the scope of this study, although the evaluation/design process outlined can be used as the

GENERAL SEQUENCING OF IN-SITU SITE DEVELOPMENT
AND RETORT MONITORING PROGRAM

Industrial Development Phase	Monitoring Design Phase
Exploration/Resource Evaluation	Initial hydrogeologic characterization
Initial Mine Plan/Retort Design	Design of hydrogeologic test program
	Conduct hydrogeologic test program
	Reevaluation--preliminary monitoring design
Dewatering/Mine Development	Gather additional data on site-specific (retort field) hydrogeologic framework
	Note changes in mine/retort design
	Final monitoring design
Retorting	Implement design for initial retort field(s)
↓ Operation	Evaluate monitoring data and monitoring design; program modification likely
Abandonment	Continue data collection/evaluation

basis for an evaluation of these sites. A general design process is the subject of the following discussions.

MONITORING WELL INSTALLATION

Groundwater flow in the study region is controlled by a complex, multilayered system of fractures, faults, and solution openings. Detailed, site-specific hydrogeologic characterization is a necessary precursor to siting and constructing effective monitoring wells. Recommendations for hydrogeologic testing, leading to design of monitor wells include the following:

1. Relatively small-scale focus in retort fields
2. Close interrelation of hydrogeologic characterization studies and exploration/resource evaluation operations
3. Iterative reevaluation and scale-up from preliminary data (exploration core holes) to aquifer testing program to provide for appropriate placement and consistent completion of testing and monitor wells
4. Iterative reevaluation of flow net to address variability in aquifer transmissivity and anisotropic conditions
5. Construction of test and monitor wells in sets to allow consistent (with regard to stratigraphic, hydrologic, and water quality conditions) well completions
6. Location of monitor wells (a) near and within the retort field and (b) downgradient along fracture lines and major axis of anistotropy
7. Multiple completion of wells within discernible aquifer subunits
8. Sample collection by pumping.

Hydrogeologic Characterization

The following general plan for hydrogeologic characterization is designed to provide needed information for the location of monitoring wells, for the design of the wells, and for the operation of the wells (see Sections 5, 9, and 10).

1. Characterization of the groundwater flow regime should focus on the retort fields directly rather than on the tract region as a whole.
2. Initial data can be obtained during site exploration/resource evaluation activities in the following manner:

a. Exploration core holes should be used as initial hydrogeologic test holes. Core size should be sufficient to allow preliminary logging and sample collection.

b. Test drilling operations should include observation and logging by a hydrogeologist; drilling logs provide indirect indication of porous and permeable zones

   -- Inflow water

   -- Loss of drilling fluid

   -- Changes in drilling rate

   -- Change in fluid level in bore hole.

c. Test hole reference elevations should be surveyed directly or sited on topographic maps to facilitate correlation between test holes.

d. Cores collected during exploration should be evaluated for hydrogeologic information. Oriented cores are preferred for identification of fracture and solution features, and testing of porosity and permeability.

e. Geophysical investigations should be pursued at this phase of development (see item 4). Depending on the location and intercorrelation results, exploratory test holes should be enlarged and used for subsequent monitoring or testing holes. Otherwise, holes should be filled with cement.

Data collected during the exploration phases should be compared to other near-tract data available, and exploration data should be intercorrelated to develop an initial picture of local variability and presence of geologic or hydrologic anomalies. These data evaluations should then form the basis for designing the more detailed testing program described below (items 3 through 7). The data collected in these early phases should be viewed as preliminary and any sampling installations as temporary.

3. Other preliminary investigations prior to more detailed testing:

   a. Measure water levels in small-diameter wells completed in core holes as well as collect water-level data during drilling efforts.

   b. Evaluate potential aquifer boundaries: locate formation outcrops, faults, and surface water bodies using field reconnaissance and aerial photography. Faults on Tract

C-a, for example, have been shown to be barriers to groundwater flow.

   c. From the above, develop preliminary flow net for retort field area. Use flow net to evaluate possible location of test and monitor wells.

4. Geophysical logs are recommended as follows:

   a. Electric - spontaneous potential (SP) and resistivity: measure of formation water resistivity, bed thickness (shales, nonshales)

   b. Elastic wave propagation - reflection (amplitude of reflected wave): indicates location of vugs and fractures, orientation of fractures, bed boundaries

   c. Radiation - neutron-gamma, gamma-gamma: indicates porosity, density, and water content

   d. Miscellaneous

      -- Temperature logs: indicate formation temperature, flow direction, relative head levels

      -- Flow meter (spinner) logs: indicate zones of fluid entry and discharge

      -- Caliper logs

      -- Fluid conductivity.

5. Aquifer characteristics are best defined by well testing methods as follows:

   a. Testing wells - From the results of the above-described initial testing, additional wells for detailed hydrogeologic testing should be sited within each proposed retort field. Aquifer tests conducted during Tract C-a and C-b baseline programs were at some distance from the proposed MIS retort fields. Additional data are available for Tract C-a as a result of short-term dewatering-reinjection program testing. These latter type of data are more site-specific to retort fields than the earlier tests and thus of more utility for monitoring design purposes. As these wells may ultimately be used for operational abandonment monitoring, the goal of this testing is to develop data allowing consistent (with regard to stratigraphic, hydrologic, and water quality considerations) well completions.

      Three or four wells should be drilled in each retort field. Two wells should be of sufficient size (minimum

8-inch casing) for aquifer testing. Other wells need only be large enough (6 inches) to accommodate smaller pumps which will be used for water quality sampling. This second set of wells will be used initially as aquifer test observation wells if initial piezometers are not properly located or are not completed in intervals to be tested. In addition, they should be used for characterization of existing water quality and subsequently for abandonment monitoring to the extent possible.

b. Aquifer testing - Utilizing information from the preliminary evaluation program and drillers' logs and geophysical testing in test and monitor well holes, individual zones should be isolated with temporary packers for aquifer testing by pumping. The purpose of such tests is to define hydrologic properties of various permeable zones, to determine interconnection between adjacent aquifer zones, and to measure water quality variations between zones.

This testing should finalize data needed for well completion and sampling design. Test wells should be evaluated for use in operation/abandonment monitoring. For use in monitoring, they should be completed and developed as described under Well Completion, p xiv. During aquifer tests, water quality sampling should be undertaken to define background water quality and to evaluate well sampling procedures for the monitoring program (e.g., length of pumping time needed to obtain a representative sample).

Test recommendations include the following:

-- Use step-discharge approach until acceptable discharge rate is identified

-- Then use constant-discharge approach

-- Use 2 or more observation wells per test, at different distances from pumping well to allow evaluation of time-drawdown and distance-drawdown relationships.

Follow general procedures in Kruseman and DeRidder (1976) or similar texts. Test should include analysis of both drawdown and recovery phases. Long-term tests are recommended

-- Until cone of depression stabilizes and does not appear to vary with continued pumping

-- Several weeks pumping may be required to adequately characterize the system. Questions regarding the technical adequacy of aquifer tests on Tracts C-a and C-b are presented in Section 5, including length of pumping and recovery periods, and an analysis of test data (such as correction for nonconstant discharge rate and choice of method for analysis of recovery priod data).

   c. Data analysis - Fully document all data collected, the rationale for selection of analysis approach; discuss assumptions relative to the system tested. Emphasis should be placed on estimating transmissivity and evaluating variability (aquifer anisotropy) of transmissivity. These evaluations should then be utilized to reevaluate preliminary flow nets to address variability of transmissivity and anisotropic conditions encountered. Anisotropic flow nets should be developed as part of existing tract baseline studies.

6. Evaluate distribution of hydraulic head with depth via:

   a. Flow net analysis

   b. Water-level changes encountered during drilling

   c. Water temperature versus depth (in well bore) data.

7. Develop detailed description of:

   a. Flow rates (transmissivity and gradient)

   b. Flow direction (horizontal and vertical)

   c. Flow boundaries, anisotropy.

Well Location

One of the goals of hydrogeologic characterization efforts is to allow description of groundwater flow patterns within and near a retort field. The purpose of this description is to locate monitoring wells so as to sample flow through and from the retort field area. Monitor wells should be located as follows:

1. Near retort field (within a few hundred feet) and within the field
2. Oriented downgradient of the MIS retorts along fracture lines and major axis of anisotropy as defined by geologic testing program
3. Accessible for sampling equipment.

Construction of new wells may be required for operation/abandonment monitoring. Wells constructed for hydrogeologic testing may not be appropriately located for inclusion in the monitoring program.

Well Completion

Phase I evaluations have indicated that well completion can play a major role in determining the nature and representativeness of groundwater quality samples. For example, deep aquifers in the Piceance Basin are composed of numerous layers of fracture and solution cavities. Most of the wells currently constructed in the Piceance Basin are open to several of these aquifer layers. Adjacent layers may differ considerably in water quality and head. Interconnection of such layers in well bores can result in mixing of waters of different water quality or in dominance (in water quality samples) of water from a layer exhibiting greater head than adjacent layers. The former condition may yield an unacceptable mixed composite of the aquifer layers. The latter is not a composite and is not truly representative of the open interval. Under such conditions, baseline water quality may not be adequately measured; and for operation/abandonment phase monitoring, groundwater flow through abandoned retorts may not be adequately represented.

For monitoring wells, multiple completions are recommended. As pumping is the recommended sample collection method, wells with minimum 6-inch-diameter casing are required to facilitate a suitable submersible pump. Pumps less than 4 inches in diameter are available. However, the depth of the wells needed for MIS retort monitoring (e.g., 600 to 700 feet to the Upper Aquifer in the Piceance Basin) is sufficiently great that larger wells are needed to avoid problems of wedging of the pump in the well.

Multiple completions of wells which can be pumped for sampling (or multiple wells completed in different intervals) are obviously more expensive than single completions. Such multiple completions are not currently being employed. However, since pumping results in sampling of a large aquifer cross section, fewer monitor wells will be needed than if bailing or other nonpumping sampling techniques are employed. These cost tradeoffs will be considered in more detail in Phase II studies.

Monitoring wells should be completed as follows:

1. Steel casing (structural properties of PVC may preclude its use for such deep wells)

2. The least costly construction approach is to leave the well open in the desired interval; such an approach (as opposed to well screening) is commonly employed for wells drilled in consolidated formations

3. The remaining segments of the well bore should be sealed with cement grout to assure lack of interconnection of sampled intervals (a cement-log should be run to verify the integrity of this seal)

4. Wells should be pumped thoroughly to remove any traces of drilling fluid or other materials which may affect water quality samples.

WELL SAMPLING PROCEDURES

Recommendations for well sampling are as follows:

1. Sampling should be by pumping
2. Samples should be collected for analysis only after the well has been developed by removal of several well volumes of water
3. Conductivity, temperature, and pH should be measured during development as a guide for identifying an appropriate time for sample collection
4. Samples should be preserved and handled in the field immediately after collection according to U.S. EPA (1974) recommendations
5. Sample holding times should be evaluated to determine the need for on-site analytical facilities
6. Annual to semiannual sampling is probably adequate prior to retort abandonment and cessation of dewatering; thereafter monthly sampling is recommended until trends are established and lower sampling frequencies can be initiated.

Sample Collection

Collection of groundwater samples for chemical analysis should be preceded by removal of water from the well bore. Sampling of deep aquifers is currently accomplished by bailing or swabbing techniques on Tracts C-a and C-b. For the deep wells to be utilized for monitoring MIS retorts, pumping is recommended. This provides for sampling a greater portion of the aquifer, thus minimizing the potential for missing or delaying the observation of mobile pollutant constituents.

For monitor well sampling, the following procedure is recommended:

1. Compile preliminary data needed for each well (or separate completion): well diameter, total depth of well. From these data the volume of water in the well (well volume) can be calculated for any given well water level. This information plus "as built" drawings for each well should be available in the field at the time of sampling.
2. Measure water level and estimate well volume
3. The pump should be set opposite and near the bottom of the perforated or open interval
4. Develop the well by removal of at least 2 to 3 well volumes from the well

5. Measure well water conductivity, temperature, and pH as often as possible during the well development procedure, but at least once per well volume discharge

6. Collect and process samples as described in the following subsection after a suitable number of well volumes have been removed and water quality of the well discharge has stabilized (as measured by pH, temperature, and conductivity).

Sample Preservation and Handling

Sample preservation and handling requirements are dictated by the nature of the constituents to be analyzed. For the recommended constituents, the holding times listed below are recommended by U.S. EPA (1974). Bottle requirements (plastic versus glass) are also provided in this reference. Filtering of samples immediately after collection is recommended with addition of chemical preservatives in the field at the time of collection or addition of preservatives to sample bottles prior to initiation of field activities.

	Preservative	Maximum holding time
General water quality constituents		
Total dissolved solids (filterable residue)	Cool, 4°C	7 days
Conductance	Cool, 4°C	24 hours
pH	Determine on site	6 hours
Alkalinity	Cool, 4°C	24 hours
Major inorganics		
Calcium, magnesium, potassium, and sodium	Nitric acid to pH < 2	6 months
Bicarbonate	Cool, 4°C*	24 hours*
Carbonate	Cool, 4°C*	24 hours*
Chloride	None required	7 days
Nitrate	Cool, 4°C	24 hours
Sulfate	Cool, 4°C	24 hours
Fluoride	Cool, 4°C	7 days
Ammonia	Cool, 4°C, sulfuric acid to pH < 2	24 hours
Phosphate	Cool, 4°C	24 hours

(continued)

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*Assumed same as alkalinity.

	Preservative	Maximum holding time
Organics		
Dissolved organic carbon	Cool, 4°C, sulfuric acid to pH < 2	24 hours
Kjeldahl nitrogen	Cool, 4°C, sulfuric acid to pH < 2	24 hours
Trace metals		
Arsenic	Nitric acid to pH < 2	6 months
Selenium	Nitric acid to pH < 2	6 months
Vanadium	Nitric acid to pH < 2	6 months
Molybdenum	Nitric acid to pH < 2	6 months
Mercury	Nitric acid to pH < 2	38 days (glass container)

The short holding times listed here will be difficult, if not impossible, to accomplish in the remoteness of the oil shale region unless on-site laboratory facilities are developed. Such an approach is recommended for the following:

- Conductance
- pH
- Alkalinity
- Carbonate
- Bicarbonate
- Chloride
- Ammonia (electrode method)
- Fluoride (electrode method).

Since it may not be feasible to meet the listed holding time requirements for many of the constituents listed (e.g., TDS, nitrate, sulfate, phosphate, DOC, and Kjeldahl nitrogen), it is recommended that testing be initiated so that more suitable holding times for the waters in question can be defined and the nature and significance of errors evaluated.

Sampling Frequency

Proper selection of well sampling frequency is a function of potential pollutant mobility, and when hard data are not available, the selection is often made by trial and error. Shallow groundwater systems commonly display response to seasonal or otherwise cyclic events of recharge and infiltration of dissolved constituents from the surface. Regional pumping patterns can also affect the variability of water quality in both deep and shallow wells. Such variability would necessitate relatively greater sampling frequencies.

The aquifers to be monitored for the impacts of abandoned MIS retorts are relatively deep and not subject to great variability from recharge events. Such influence of cyclic events is usually attenuated during slow passage through the aquifer. Hence, a somewhat low sampling frequency is appropriate.

Another consideration is the sequence of events leading to abandonment, namely, mine-retort operation, termination of retorting, termination of dewatering, and recovery of aquifer water levels in the mine-retort area. During the operational phase, particularly when dewatering is appreciable, no releases would be anticipated from the MIS retorts. Thus, low-frequency sampling (e.g., annual) would be adequate. If dewatering is via wells (rather than strictly from the mine itself), the dewatering wells (sampled individually) may be an acceptable location for sampling. Any groundwater flow within the retort field during this dewatering phase would be dominated by and directed toward the dewatering wells. Thus, any appreciable groundwater movement in the retort interval would be effectively sampled by these wells.

During the time from cessation of dewatering through stabilization of water levels, the groundwater system would be in a state of flux and rapid changes in water quality may occur. During this period, more frequent sampling is recommended. Initially, monthly sampling is appropriate to establish patterns of temporal variability. This frequency can then probably be diminished to semiannual and then perhaps to annual as time trends are established. Several years may pass before these low frequencies are appropriate.

SAMPLE ANALYSIS

Recommendations for sample analysis are as follows:

1. Routine monitoring of constituents listed in the preceding discussion of sample preservation and handling
2. More extensive sample collection and analysis (such as unique indicators discussed in Section 10) should the routine sampling program indicate an impact of MIS retorts on groundwater quality
3. Use of standard analytical methods.

The constituents listed in the preceding discussion of sample preservation were selected for routine monitoring because high levels are expected should materials leach from MIS retorts. In addition, constituents include those which allow data checks (TDS-conductivity, cation-anion balance, etc.) to be performed as a quality control measure. Should this routine monitoring program indicate an impact of MIS retorts on groundwater quality, more extensive analysis of samples is recommended. This analysis should include the sets of possible unique indicators presented in Section 10 of this report.

This recommended list of constituents includes fewer constituents than the analysis sets of presently implemented monitoring programs, such as outlined in Section 9 of this report. This shortened list should allow detection of groundwater quality impacts due to MIS retorts while economizing on analytical needs.

Other sets of constituents, such as various organic fractionations and stable isotope ratios, need to be evaluated further, particularly the interpretation of such data with regard to indicating the impact of oil shale byproducts. Standard analytical methods, such as presented by U.S. EPA (1974) or in Standard Methods (American Public Health Association, 1976) should be employed.

PHASE II STUDIES

A preliminary monitoring design/implementation framework has been developed and is outlined above. Another product of the analysis leading to this preliminary design is the identification of areas of uncertainty with regard to implementation of groundwater quality monitoring programs for MIS retorts. Phase II study plans have been developed to supplement the information base presented in this report and to provide additional cost-effectiveness bases for developing a monitoring design guideline. To the extent possible, these data collection efforts will be coordinated with other research efforts.

Three basic tasks have been identified for the Phase II studies. These tasks are considered in detail in Section 11 of this report:

1. Task 1. Sampling Evaluation
    a. Well sampling approaches
    b. Well construction
    c. Sample handling and preservation
2. Task 2. Hydrogeologic Characterization
    a. Geophysical methods
    b. Other testing procedures
    c. Evaluation of mine development phase data
3. Task 3. Characterization of In-Situ Retort Source
    a. Chemical analysis
    b. Leaching and mobility.

Task 1 includes assessment of various sampling factors which influence water quality data. Various sample collection methods have been used during oil shale tract baseline surveys. Tests of bailing versus pumping and of the effect of various pumping procedures will be conducted, as these factors influence water quality samples. Because of the relative remoteness of the study region, meeting current EPA specifications of sample holding time is very difficult. Tests to determine the influence of various holding times will be conducted.

Well construction has been shown to greatly influence water quality in the oil shale region. During Phase II, the data base on methods used in Piceance Basin will be extended beyond tract-related operations. Well size, annular sealing, casing material, perforation, and well development methods will be considered. Probable influences on water quality samples will be evaluated and cost data compiled for alternative approaches. Water quality data collected before and after the current Tract C-b recompletion program will be compiled and compared.

Task 2 studies will supplement Phase I evaluations of methods for characterizing MIS retort sites. Such characterization is an essential element for siting monitor wells and for the design of the wells (e.g., perforated interval) to obtain consistent and representative samples. Geophysical and other testing methods will be evaluated and ranked relative to cost, potential effectiveness, and availability of testing equipment in the oil shale region. Data developed during Tracts C-a and C-b mine development (e.g., fracture mapping) will be compiled and used to assess the geophysical and hydrological testing procedures utilized on the tracts.

Task 3 is a continuation of preliminary assessments related to the selection of constituents for monitoring. These tests and evaluations of leaching characteristics and mobility/attenuation mechanisms will be used to support final recommendations of constituents to be monitored based on likelihood of meeting previously outlined monitoring goals and on cost considerations.

Phase II studies will develop data for final monitoring recommendations. The basic issues of how, where, and what to sample will be considered in Tasks 1, 2, and 3 as outlined above. The final recommendations will be presented in a format allowing planning and implementation of groundwater quality monitoring programs by the various industrial and regulatory groups involved in monitoring.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS AND SYMBOLS

AA	atomic absorption spectroscopy
AOSS	Area Oil Shale Supervisor
API	American Petroleum Institute
bbl	barrel(s)
BPSD	barrels per stream day
°C	degrees Centigrade
cfs	cubic feet per second
DDP	Detailed Development Plan
DOE	Department of Energy
EF	enrichment factor
EPA	U.S. Environmental Protection Agency
°F	degrees Fahrenheit
FGD	flue-gas desulfurization
ft	foot, feet
ft^2	square foot, square feet
g	gram(s)
GC	gas chromatography
GC/MS	gas chromatography/mass spectroscopy
gm/cc	grams per cubic centimeter
gpm	gallons per minute
HPLC	high-pressure liquid chromatography
HPTLC	high-pressure thin-layer chromatography
ICP	inductively coupled plasma emission spectroscopy
INAA	instrumental neutron activation analysis
lb/hr	pounds per hour
LERC	Laramie Energy Research Center
LTPD	long tons per day
MBAS	methylene blue active substances
md	millidarcy
MDP	modular development phase
meq/l	milliequivalents per liter
mg/l	milligrams per liter
MIS	modified in situ
mi/yr	miles per year
ml	milliliter(s)
MMSCFD	million standard cubic per day
NPDES	National Pollution Discharge Elimination Center
PAH	polynuclear aromatic hydrocarbons

ABBREVIATIONS (continued)

pCi/l	picocuries per liter
PNA	polynuclear aromatics
POM	polycyclic organic matter
PVC	polyvinyl chloride
RBOSP	Rio Blanco Oil Shale Project
SMSS	spark source mass spectrometry (spectroscopy)
SP	spontaneous potential
T	transmissivity

TLC	thin-layer chromatography
TOSCO	The Oil Shale Company
TPD	tons per day
TPY	tons per year
USGS	U.S. Geological Survey
µg/l	micrograms per liter
µmho	micromho(s)
µmho/cm	micromhos per centimeter

CHEMICALS, IONS, CONSTITUENTS

Al	aluminum
Ag	silver
As	arsenic
B	boron
Ba	barium
Be	beryllium
Bi	bismuth
BOD	biological oxygen demand
Br	bromine
C	carbon
C_4	four-carbon hydrocarbon
Ca, Ca^{2+}	calcium
$CaCO_3$	calcium carbonate
CaF_2	fluorite

CaO	lime
Cd	cadmium
Ce	cerium
CN^-	cyanide
Co	cobalt
CO_2	carbon dioxide
CO_3, $CO_3^=$	carbonate
COD	chemical oxygen demand
Cr	chromium
Cs	cesium
Cu	copper
DOC	dissolved organic carbon
Dy	dysprosium
Er	erbium

CHEMICALS, IONS, CONSTITUENTS (continued)

Eu	europium
F	fluorine
Fe	iron
Fe^{3+}	ferrous iron
$Fe(SCN)_x$	ferric thiocyanite
Ga	gallium
Gd	gadolinium
Ge	germanium
H_2O	water
H_2S	hydrogen sulfide
HC	hydrocarbon
HCO_3, HCO_3^-	bicarbonate
Hf	hafnium
Hg	mercury
$HgCl_2$	mercuric chloride
Ho	holmium
I	iodine
K	potassium
$K_2Cr_2O_7$	potassium dichronate
La	lanthanum
Li	lithium
Lu	lutetium
Mg	magnesium
Mn	manganese
Mo	molybdenum
N	nitrogen
Na	sodium
$NaAl(OH)_2CO_3$	dawsonite
$NaHCO_3$	nahcolite
NaCl	halite
Nb	niobium
NH_3	ammonia
NH_3-N	ammonia nitrogen
NH_4^+-N	ammonium nitrogen
Ni	nickel
NO_x	nitrous oxides
NO_2-N	nitrite nitrogen
NO_3	nitrate
NO_3-N	nitrate nitrogen
O	oxygen
OH, OH^-	hydroxide
P	phosphorus
Pb	lead
Po	polonium
PO_4	phosphate
Pr	praseodymium
Rb	rubidium
R-CO_2	hydrocarbon with CO_2 group attached
R-NH_2	hydrocarbon with NH_2 group attached

CHEMICALS, IONS, CONSTITUENTS (continued)

S	sulfur
S^-	sulfide
$S_2O_3^=$	thiosulfate
$S_4O_6^=$	tetrathionate
Sb	antimony
Sc	scandium
SCN^-	thiocyanate
Se	selenium
Si	silica
SiO_2	silica dioxide
SO_4, $SO_4^=$	sulfate
Sr	strontium
Ta	tantalum
Tb	terbium
TDS	total dissolved solids
Te	tellurium
Ti	titanium
Tl	thallium
Tm	thulium
TOC	total organic carbon
U	uranium
V	vanadium
W	tungsten
Y	yttrium
Yb	ytterbium
Zn	zinc
Zr	zirconium

FORMULAE ABBREVIATIONS

T_{max}	maximum transmissivity
a	major axis of drawdown ellipse
b	minor axis of drawdown ellipse
T_e	effective transmissivity
T_{min}	minimum transmissivity
I_1	major isotope
I_2	minor isotope
δ	variation in isotope abundance
M_i	mass of ith constituent
m	mass of spent shale
$\overline{C}_i$	average concentration of ith constituent
K	aquifer permeability
i	groundwater level gradient
c/c_0	concentration relative to standard concentration, c_0

FORMULAE ABBREVIATIONS (continued)

$(C_g)_i$	concentration of ith constituent in groundwater
V	pore volume
α	aquifer porosity
L	flow distance
a	dispersion coefficient
h_2-h_1	head difference at locations 1 and 2
r_2-r_1	difference in radius measurements at locations 1 and 2
W	flow width
Q	flow rate (ft^3/day)

ENGLISH/METRIC SYSTEM

° Fahrenheit	(°Centigrade x 9/5) - 32
1 gallon	3846.2 cubic centimeters 3.86 liters
1 barrel	0.16 cubic meter
1 cubic yard	0.77 cubic meter
1 cubic foot	0.028 cubic meter
1 acre-foot	1250 cubic meters
1 pound	0.0005 tonne (metric ton) 487.8 grams
1 acre	0.0004 hectare
1 quart	0.9463 liter
1 foot	0.305 meter
1 square mile	2.59 square kilometers
1 ton (short)	0.909 tonne (metric ton)

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SECTION 1

INTRODUCTION TO MONITORING AREA

INTRODUCTION

Synthetic petroleum products recovered from western oil shales are expected to play an important part in supplying future energy needs of the United States. Various estimates of the magnitude of western oil shale reserves have been made. The U.S. Geological Survey estimates that an equivalent of about 4000 billion barrels* of oil are contained in the oil shales of the Green River Formation of Utah, Colorado, and Wyoming (Table 1-1). These oil shale resources account for 80 percent of the known world resources but, of course, are not completely recoverable. Recoverable resources are a function of mining and retorting technology and economics, but may amount to about 1800 billion barrels of oil (Hendricks and Ward, 1976). As the estimated remaining world ultimate oil resources are about 2000 billion barrels (Tiratsou, 1976), of which less than 150 billion barrels are in the United States, western oil shale is clearly a significant energy resource.

TABLE 1-1. OIL SHALE RESERVES IN THE GREEN RIVER FORMATION[a]

Shale grade (gallons oil/ton)	Uinta Basin, Utah (billions of barrels)	Piceance Creek Basin, Colorado (billions of barrels)	Green River Basin, Wyoming (billions of barrels)	Total (billions of barrels)
25-65	90	500	30	620
10-25	230	800	400	1,430
5-10	1,500	200	300	2,000
	1,820	1,500	730	4,050

[a] From Hendrickson, 1975.

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* See pp xxxvi for conversion to metric units. English units were used in this report because of their current usage and familiarity in industry and the hydrology-related sciences.

FEDERAL PROTOTYPE LEASE DEVELOPMENT

The current Federal Prototype Oil Shale Leasing Program, administered by the U.S. Department of Interior, was initiated in 1969. Program planning and environmental evaluation efforts by various government interagency and industry groups culminated in preparation of a draft environmental impact statement in 1971. Informational core hole drilling by firms interested in obtaining oil shale leases was conducted in the 1971 through 1973 period. This led to nomination of twenty potential lease tracts in Colorado, Utah, and Wyoming. The Department of Interior selected six tracts for the prototype leasing program. The environmental impact statement was finalized in 1973. Later in 1973, the first lease sale was initiated. In January 1974, successful bidders for the two Colorado lease tracts (C-a and C-b) and for two Utah tracts (U-a and U-b) were announced. No bids were received on the proposed Wyoming lease tracts.

Environmental baseline and operation design studies were conducted over the two years following the lease initiation. In 1976, Detailed Development Plans (DDP) were submitted for both Tracts C-a and C-b. The initial DDP for Tract C-a called for open pit mining, surface retorting, and off-tract locations for processing facilities, overburden and processed shale disposal. A number of serious problems, particularly approval for off-tract disposal of wastes could not be resolved and a lease suspension was requested. This suspension was granted in September 1976. During the suspension, a revised DDP for Tract C-a was prepared calling for modified in-situ (MIS) development plus surface retorting of the oil shale mined from development of the MIS retorts. This revised DDP was submitted in May 1977 and was subsequently approved by the Area Oil Shale Supervisor (AOSS). As described in Section 2, a modular development program was proposed and has been initiated on Tract C-a.

Initial development plans on Tract C-b (by Ashland Oil, Inc., and Shell Oil Company) were submitted in February 1976. This plan called for a deep mining and surface retorting (and disposal) operation. Development was suspended later in 1976. In November of that year, Shell withdrew from the C-b Oil Shale Project and Ashland formed a new venture with Occidental Oil Shale, Inc. A revised DDP proposing MIS operations was submitted in February 1977. Site development was initiated in the fall of 1977.

The economic feasibility for retorting oil shales in situ looks promising, based on recent tests conducted by Occidental Oil Shale, Inc. Serious environmental impacts may result from in-situ retorting and the on-site upgrading and processing of the recovered oil. These impacts should be anticipated and avoided to the extent possible--any decision to accept environmental damage, for example, a reduction in groundwater quality, should be a conscious one based on the best information and analysis available.

Development of this resource so far has taken place only on a prototype scale because accessible supplies of oil and gas have been available at a lower development cost. The Nation's future energy needs are so large, however, that it is necessary to examine the possibility of supplementing our conventional domestic oil and gas deposits with synthetic fuels derived from oil shale.

Monitoring of groundwater quality impacts associated with in-situ oil shale development will be difficult. Retort waters produced by small-scale in-situ operations have resulted in the identification of a wide spectrum of potential pollutants. Research to date indicates that many of these pollutants have only recently been classified, while others are still under investigation. It is not clear if the quality of the retort waters from small-scale in-situ retorting will be similar to those waters produced by large-scale commercial in-situ retorts.

Shale deposits in the Piceance Basin that can potentially be exploited by in-situ technologies underlie an area of considerable topographic variation that is largely undeveloped. A wide range in both hydrologic and geologic conditions occurs throughout the area containing the deposits. Several in-situ technologies are available, each of which could have characteristic impacts. There has not been sufficient experience with the various retorting methods to determine which is the most suitable in terms of minimizing environmental harm in the Piceance Basin. It may appear at first glance that in-situ retorting has less potential for impact to the environment than surface retorting; however, the long-term impact to the subsurface environment may prove this assumption to be wrong.

Groundwater presently plays a key role in satisfying U.S. water needs for municipal, agricultural, and industrial uses. In addition, groundwater discharges to streams and rivers comprise a significant percentage of surface water supplies. During low flow periods, almost all surface flow results from groundwater discharges. This interaction between surface water and groundwater is an important consideration in the evaluation of groundwater pollution; subsurface contamination may ultimately affect both surface water and groundwater users.

The Federal Water Pollution Control Act Amendments of 1972 (P.L. 92-500) and the Safe Drinking Water Act of 1974 (P.L. 92-523) provide for protection of groundwater quality. These mandates call for programs to prevent, reduce, and eliminate pollution of both navigable waters and groundwater and for particular protection of drinking water resources. Similar goals are embodied in the Toxic Substances Control Act of 1976 and the Resource Conservation and Recovery Act of 1976. The national responsibility for these various activities is given to the U.S. Environmental Protection Agency (EPA). Various State agencies also have similar responsibilities via State enabling legislation.

The mandates of P.L. 92-500 necessitate implementation of a system for detecting and delineating groundwater pollution before points of use are affected and preferably before pollutants enter the subsurface. Monitoring approaches for these requirements are in marked contrast with more traditional programs aimed at sampling water quality and quantity at the point of supply for a specific use. The design problem described in this report has been addressed using a systematic approach for predictive groundwater quality monitoring developed by General Electric--TEMPO of Santa Barbara, California

(Table 1-2). This stepwise methodology includes identification of pollution sources, their associated pollutants, and the potential for mobility of these pollutants in the specific hydrogeologic framework of the study area.

TABLE 1-2. TEMPO MONITORING METHODOLOGY

Step	Description
1	Select Area for Monitoring
2	Identify Pollution Sources, Causes, and Methods of Disposal
3	Identify Potential Pollutants
4	Define Groundwater Usage
5	Define Hydrogeologic Situation
6	Describe Existing Groundwater Quality
7	Evaluate Infiltration Potential of Wastes at the Land Surface
8	Evaluate Mobility of Pollutants from the Land Surface
9	Evaluate Attenuation of Pollutants in the Saturated Zone
10	Prioritize Sources and Causes
11	Evaluate Existing Monitoring Programs
12	Identify Alternative Monitoring Approaches
13	Select and Implement the Monitoring Program
14	Review and Interpret Monitoring Results
15	Summarize and Transmit Monitoring Information

OIL SHALE MONITORING DESIGN PROGRAM

This report presents the results of a monitoring design study of in-situ oil shale development. The approach used is the general methodology outlined in Table 1-2. In particular, this report deals with an initial pass through methodology steps 1 through 13, although step 13 is not fully implemented. The methodology, in general, and its application to monitoring design problems are described in several other reports (Todd et al., 1976; Slawson, 1979; and Everett, 1979) and will not be presented here in detail.

The potential for development of oil shale resources in the Western United States is briefly summarized in the preceding paragraphs. Because of the magnitude of these resources and the likely expansion of this new industry to meet ever-accelerating energy needs of the United States, proposed oil shale developments were reviewed by the EPA to identify candidate study areas.

After a review of the proposed developments, the Utah Federal Prototype Lease Tracts were considered generally representative of deep mining-surface retorting oil shale developments. An assessment of this development is the subject of other reports completed for this study (Slawson, 1979, 1980). Many of the results of the Utah study are transferable to the design of groundwater quality monitoring programs for similar oil shale enterprises both in Utah and in other parts of the Western United States. For this reason, the study presented in this report focuses on the components of in-situ operations which have no counterpart in deep mine-surface retorting operations.

The assessments outlined in the following sections of this report focus on modified in-situ development as proposed for Federal Prototype Lease Tracts C-a and C-b in Colorado (Figure 1-1). The results of this evaluation should, in general, be applicable to other sites in the oil shale region of the Western United States. However, site-specific features of Tracts C-a and C-b, which are considered here, produce results which, in detail, may not be characteristic of other locations. In addition, changes in development plans, such as implementation of alternative processes or control technologies, may alter these assessments.

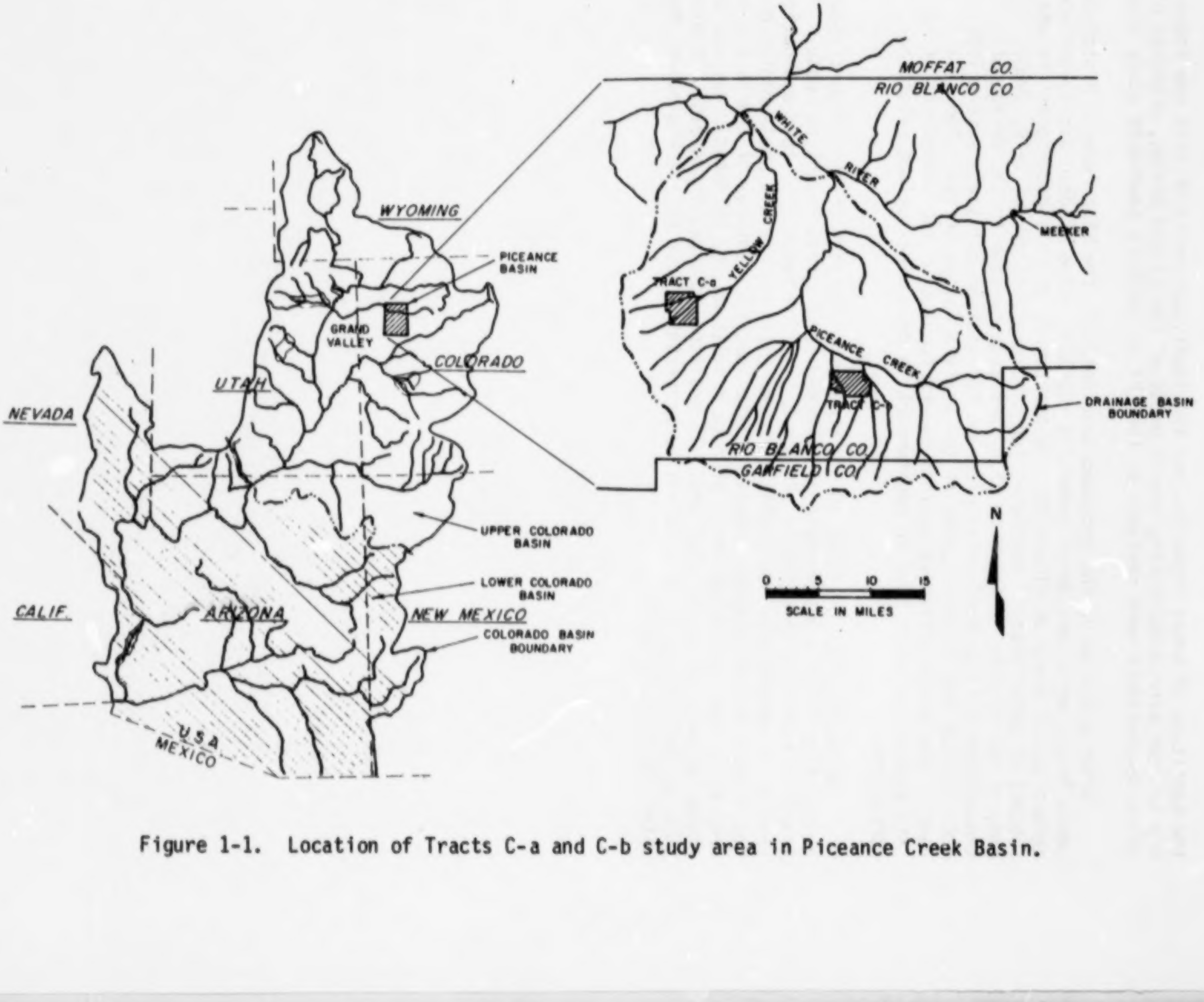
MOFFAT CO.
RIO BLANCO CO.
WHITE RIVER
YELLOW CREEK
MEEKER
TRACT C-a
PICEANCE CREEK
TRACT C-b
DRAINAGE BASIN BOUNDARY
RIO BLANCO CO.
GARFIELD CO.
N
0 5 10 15
SCALE IN MILES
WYOMING
PICEANCE BASIN
GRAND VALLEY
COLORADO
UTAH
NEVADA
UPPER COLORADO BASIN
LOWER COLORADO BASIN
CALIF.
ARIZONA
NEW MEXICO
COLORADO BASIN BOUNDARY
USA
MEXICO

Figure 1-1. Location of Tracts C-a and C-b study area in Piceance Creek Basin.

SECTION 2

POTENTIAL SOURCES OF POLLUTION AND METHODS OF DISPOSAL

OVERVIEW OF MODIFIED IN-SITU DEVELOPMENT

This study addresses MIS oil shale development such as proposed for Federal Prototype Lease Tracts C-a and C-b. The MIS process consists basically of two steps (Figure 2-1): (1) a retort cell is formed by mining 15 to 20 percent or more of the oil shale zone and rubbling the remaining resource using explosives, and (2) retorting the rubblized oil shale in place (in situ). In some areas, dewatering of aquifers may be required to accomplish these operations. The mining and rubbling phase produces sufficient void space in the retort to allow adequate flow of input and product fluids through the retort during operation. Combustion is initiated at the top of the retort by injection of oxygen (air) and heat (e.g., from gas burners). As the flame front proceeds down through the retort, residual carbon in the spent oil shale becomes the major fuel source for retorting. After this process is sufficiently underway, the external heat source is removed. Inflow of oxygen (air) is continued and may be mixed with steam or retort off-gas to control the combustion reaction.

During retorting, the organic kerogen in oil shale is thermally decomposed (at 800° to 900°F) to form various hydrocarbon products. An operating retort is characterized by four zones (Figure 2-1):

- Burned or spent shale zone
- Combustion zone
- Retorting and vaporization zone
- Vapor condensation zone.

During the retort burn sequence, temperatures may reach 2000°F in some zones.

The products of in-situ retorting include gaseous (off-gas) and liquid (shale oil) hydrocarbon products, retort water (formed during the combustion-pyrolysis reaction) and spent or processed shale material. The product gas, shale oil, and retort water are brought to the surface for use, treatment, transportation, and/or disposal. The spent shale remains underground.

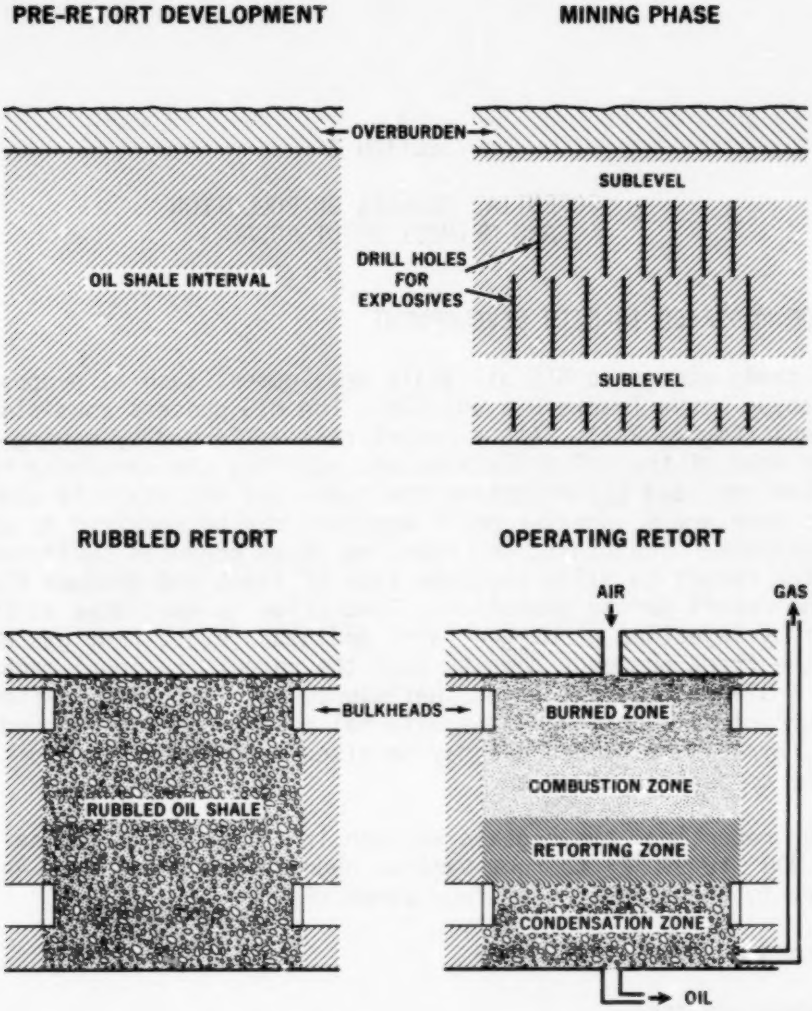
PRE-RETORT DEVELOPMENT
MINING PHASE
OVERBURDEN
SUBLEVEL
OIL SHALE INTERVAL
DRILL HOLES FOR EXPLOSIVES
SUBLEVEL
RUBBLED RETORT
OPERATING RETORT
AIR
GAS
BULKHEADS
BURNED ZONE
RUBBLED OIL SHALE
COMBUSTION ZONE
RETORTING ZONE
CONDENSATION ZONE
OIL

Figure 2-1. Generalized development of modified in-situ retort.

The oil shale mined from each MIS retort can be retorted at the surface (as proposed for the commercial phase of Tract C-a) or disposed on the surface as waste rock.

Potential sources of impact on groundwater quality from MIS development, such as proposed for Tracts C-a and C-b, are summarized in Table 2-1. Methods of material treatment, handling, and disposal are also listed. The following discussions provide more detail on these proposed operations.

TABLE 2-1. SUMMARY OF POTENTIAL SOURCES OF GROUNDWATER QUALITY IMPACT, TRACTS C-a AND C-b[a]

Source	Tract C-a		Tract C-b	
	Method of disposal	Amount	Method of disposal	Amount
Waste rock from mine development, etc.	Surface disposal pile, soil cover, revegetation	~4,000 TPD	Surface disposal pile	Included under raw shale source
Raw shale	Surface disposal (MDP, initial commercial phase)	~36,000 TPD	Surface disposal in Cottonwood Gulch, revegetation	41,000 TPD
	Surface temporary storage before retorting during full commercial operation	100,000 tons storage		
Dewatering or mine water	- Reinject - Potable water treatment (Upper Aquifer water) - Fire protection, process water, etc. - Storage and evaporation	Dewatering-17 cfs Mine water seepage-8 cfs	- Water treatment for utility, power generation, etc. - Unlined pond storage; evaporation, reinjection, or treatment and release - Use for dust control	1,700 gpm
Processed shale				
In situ	Left in place	9.8 to 14.4 x 10^8	Left in place	1.5 to 2.2 x 10^9
Surface retorting	- Surface disposal pile - Slurry injection into abandoned retorts	310x10^6 cubic yards (36,000 TPD)	No final decision on surface retorting	--
Retort water	Evaporation, combustion, treatment, and use for dust control or moistening spent shale	In situ ~57,000 BPSD	Pond storage, evaporation	~27,000 BPSD
		Surface retorts ~500 TPD		
Oily water treatment	Water to foul water stripping, sludge to TOSCO II retorts	Water ~57,000 BPSD; sludge unknown	Pond storage-see retort water	Uncertain
Foul (retort) water stripping	Distillate to steam generation, stripped water to shale moistening, acid gas to sulfur recovery	Uncertain; see oily water treatment	Uncertain	Uncertain
Raw water treatment	Line sludge and spent zeolites to surface of processed shale pile	Line sludge 870 TPY; spent zeolites 3 TPY	Domestic water hauled in at present	Uncertain

(continued)

TABLE 2-1 (continued)

Source	Tract C-a		Tract C-b	
	Method of disposal	Amount	Method of Disposal	Amount
Cooling water blowdown	Blowdown surge pond, evaporation	Unknown	Discharge to lined pond, evaporation	100 gpm
Sanitary wastewater	Discharge to mine service water pond, sewage treatment plant	Unknown	Unknown	Unknown
Oil treatment and upgrading	No upgrading except addition of flow additives	--	Package plant	
Sulfur catalysts from recovery	Temporary storage, truck transport; return to manufacturers when spent	265 LTPSD; 53 TPY	None required by FGD (Ca-sulfite) treatment	92.2 LTPSD
Tankage storage				
Shale oil	--	50,000 bbl	Unknown	Unknown
Naphtha	--	70,000 bbl		
Heavy oil	--	140,000 bbl		
Gas oil	--	1,000 bbl		
Fuel oil	--	21,000 bbl		
Ammonium-nitrate	--	525 tons		
Runoff	Storage in mine service area retention pond, evaporation, dust control, etc.	Variable	Storage in catchment ponds, evaporation, dust control, compaction of disposal piles	Variable
Disturbed areas	Most reclaimed (1,454 acres)	1,759 acres	Most reclaimed	1,456 acres
Explosives	Residues left in situ, surface storage piles	Residue unknown; 52 tons per day used	Residues left in situ, surface disposal piles	Unknown

---

[a] These data were taken from the modified development plan submitted by Rio Blanco Oil Shale Company (1977a) and C-b Shale Oil Venture (1977a). More recent reevaluation and redesign of programs leading to commercial operations are not discussed here in detail. They will be considered in subsequent phases of this project as they affect potential groundwater impacts and monitoring needs.

DEVELOPMENT SUMMARY--TRACT C-a

Introduction

The developers of Tract C-a, Rio Blanco Oil Shale Project (RBOSP), will employ a modular program to prove the technical, environmental, and economic feasibility of the MIS process prior to full-scale commercial operations (RBOSP, 1977a).

The C-a modular development phase (MDP) was initiated in 1977 to gain operating experience, improve process efficiency, confirm capital and operating cost estimates, and verify the environmental integrity of the mining and processing operations.

The commercial phase is the planned operation of a full-scale commercial complex beginning in 1987 and continuing for approximately 30 years. Production could eventually be approximately 76,000 BPSD, with 57,000 BPSD being produced by modified in-situ retorting and 19,000 BPSD from surface retorting. Higher rates of production are, or will also be, considered for Tract C-a.

The 10-year MDP is described in detail in the modified DDP (RBOSP, 1977a). The commercial phase design and operation are conceptual in nature, but sufficient information is available on the commercial phase for the purposes of this monitoring design study.

RBOSP anticipates modification of operational environmental control and monitoring programs as necessary to include more efficient ways of developing oil shale with minimal environmental impact. As stated by RBOSP (1977a), protection of the three principal components of the environment will be accomplished in the following manner:

- Water quality control will be achieved, if feasible, through the implementation of a zero surface discharge concept.

- Air quality control will be achieved by using equipment and facilities designed to minimize adverse pollutant emissions and by applying the best technology available to control any emissions that cannot otherwise be reduced by design changes.

- RBOSP's objective will be to avoid or minimize land disturbance wherever practicable. Rehabilitation of disturbed land will be undertaken through a program incorporating site preparation, erosion control, and revegetation.

Detailed plans for groundwater quality control have not been finalized. Options include spent retort isolation by grouting or other procedures, and purposeful leaching of the in-situ retort zone (adding water to the burn zone and recovering leachate for treatment). Such options are being evaluated at this time, but detailed prediction of results is extremely unlikely due to lack of experience with the in-situ development operations and the complexity of the geologic and hydrogeologic system of the Piceance Creek Basin.

Project Description

The proposed development plan consists of a rubblized in-situ extraction process for recovery of oil from oil shale, a modified sublevel caving method of mining, on-tract surface retorting, and on-tract disposal of processed shale (RBOSP, 1977a).

A schematic of the MIS operation envisioned on Tract C-a, including modular and commercial phases is shown in Figure 2-2. Proposed retort development is summarized as follows:

Development phase	Retort no.	Dimensions (feet)
Modular	1, 2	30 x 30 x 140
	3, 4	50 x 50 x 140
	5	100 x 150 x 400
	6	150 x 300 x 700
Commercial	---	150 x 300 x 750

Plans for the MDP were modified in mid-1979 to include the following retort sequence:

Retort	Description (dimensions in feet)
0	30 x 30 x 200
1	60 x 60 x 400
2	Either a pair of 60- x 60- x 400-foot retorts burned in sequence or together, or a single large retort with dimensions of 60 x 150 x 400 feet
3+	Additional retorts as tall as feasible up to 700 feet (nominal commercial size)

In addition, mining to produce retort void-space will be from a single sublevel (sublevel G) at the bottom of the retort rather than from several sublevels. Blast holes will be drilled from the surface or upper sublevels through the retort zone. After initial rubblizing, additional rock may be mucked out to optimize the void volume and rubble size.

Retorts proposed for the MDP will be developed, rubblized, and burned in a sequential manner as the in-situ process is demonstrated, operational parameters defined, mining methods tested, and the operation generally optimized.

Commercial phase production plans include an equivalent of four retorts burning simultaneously at an average burn rate of 14 feet per day. Operations will involve rubblizing retorts, transferring the resulting 20-percent volume of mined oil shale to a surface ore stockpile, and delivering mine water, retort exhaust gas, and shale oil to surface transfer points.

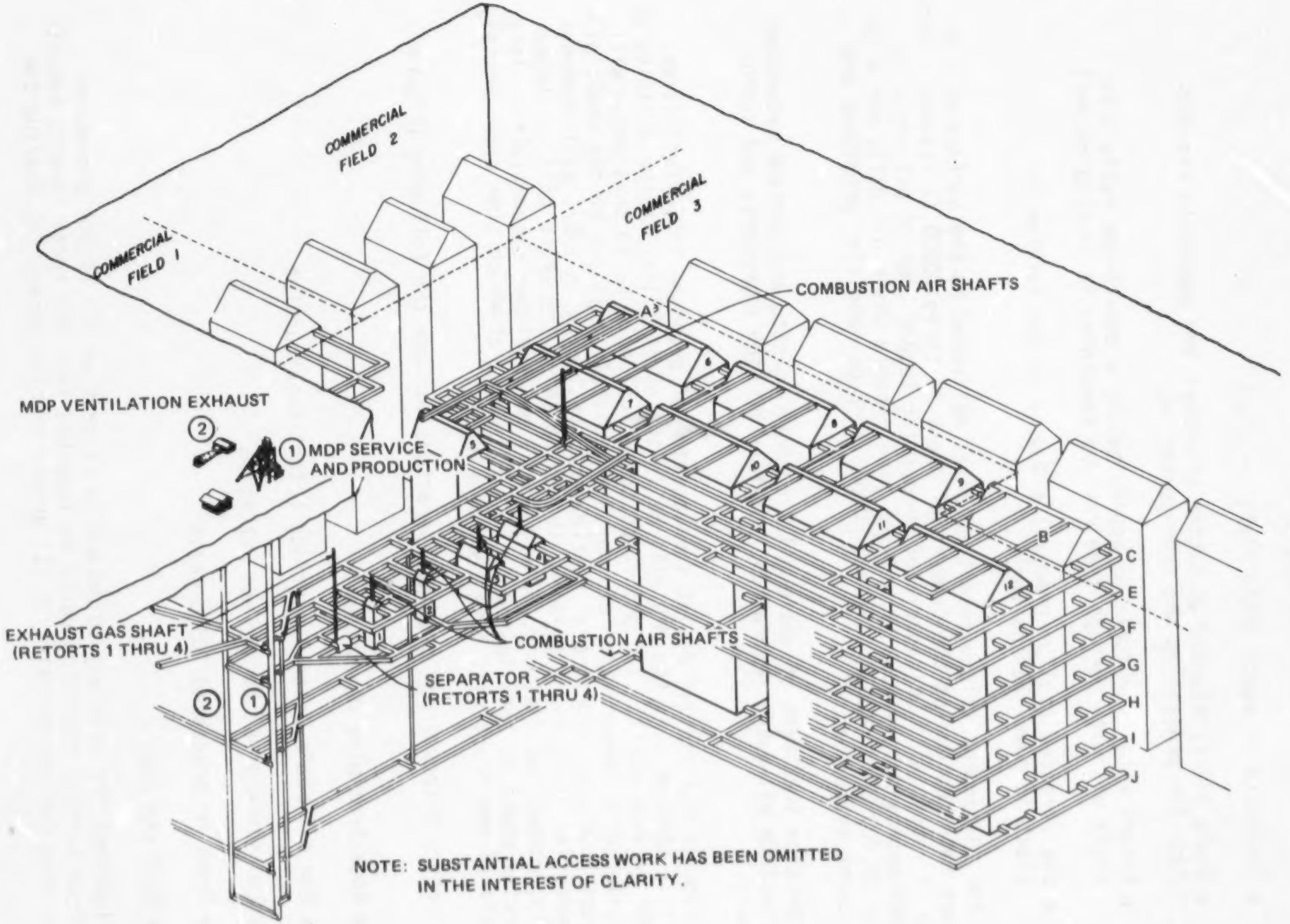
COMMERCIAL FIELD 1
COMMERCIAL FIELD 2
COMMERCIAL FIELD 3
COMBUSTION AIR SHAFTS
A
B
C
E
F
G
H
I
J
5
6
7
8
9
10
11
12
MDP VENTILATION EXHAUST
②
① MDP SERVICE AND PRODUCTION
EXHAUST GAS SHAFT (RETORTS 1 THRU 4)
COMBUSTION AIR SHAFTS
SEPARATOR (RETORTS 1 THRU 4)
② ①
NOTE: SUBSTANTIAL ACCESS WORK HAS BEEN OMITTED IN THE INTEREST OF CLARITY.

Figure 2-2. Schematic layout of mine access and modified in-situ retorts (RBOSP, 1979a).

Operational options include injection of air alone and air plus steam or water. Products of MIS retorting are:

- Processed or spent shale (left in situ)
- Shale oil (collected at bottom of retort and pumped to the surface for processing and transportation)
- Retort water (produced on approximately a one-to-one ratio with shale oil with perhaps some residue remaining in in-situ retort)
- Gas [treated (sulfur removal) and used in gas turbine for electric power generation].

The 20-percent volume retort material delivered to the surface will be surface retorted during the commercial phase in three TOSCO II retorts. Each TOSCO II retort will be capable of processing 12,000 tons of oil shale to produce approximately 6300 barrels of pipelineable shale oil daily for a total of 19,000 BPSD (RBOSP, 1977a). Other surface retorting processes are also being evaluated.

On-site treatment of shale oil from both in-situ and surface retorting will include oil-water separation, addition of flow improvers, and sulfur recovery.

Figures 2-3 and 2-4 depict the location of proposed RBOSP facilities. Retorts 1 through 5 in the MPD will be in the shaft pillar in the vicinity of the MDP service shaft. The prototype commerical retorts in this phase will be developed in commercial field no. 3 immediately adjacent to the shaft pillar east boundary. Commercial development, beginning in 1987, will commence in commercial field no. 1 adjacent to and north of the shaft pillar. Subsequently, commercial fields 2, 3, and 4 will be developed sequentially. This commercial phase is anticipated to last 30 years, at which time approximately one-half of the tract will have been developed.

Surface disposal and storage operations include the following (Figure 2-4):

- Rock from mine development
- Raw oil shale prior to surface retort construction
- Raw shale prior to surface retorting
- Spent or processed TOSCO shale
- Soil storage.

Investigations are underway to determine if part or all of the processed shale from surface retorting could be injected into the spent in-situ retorts by slurrying for the purposes of (1) ground stabilization, (2) sealing the

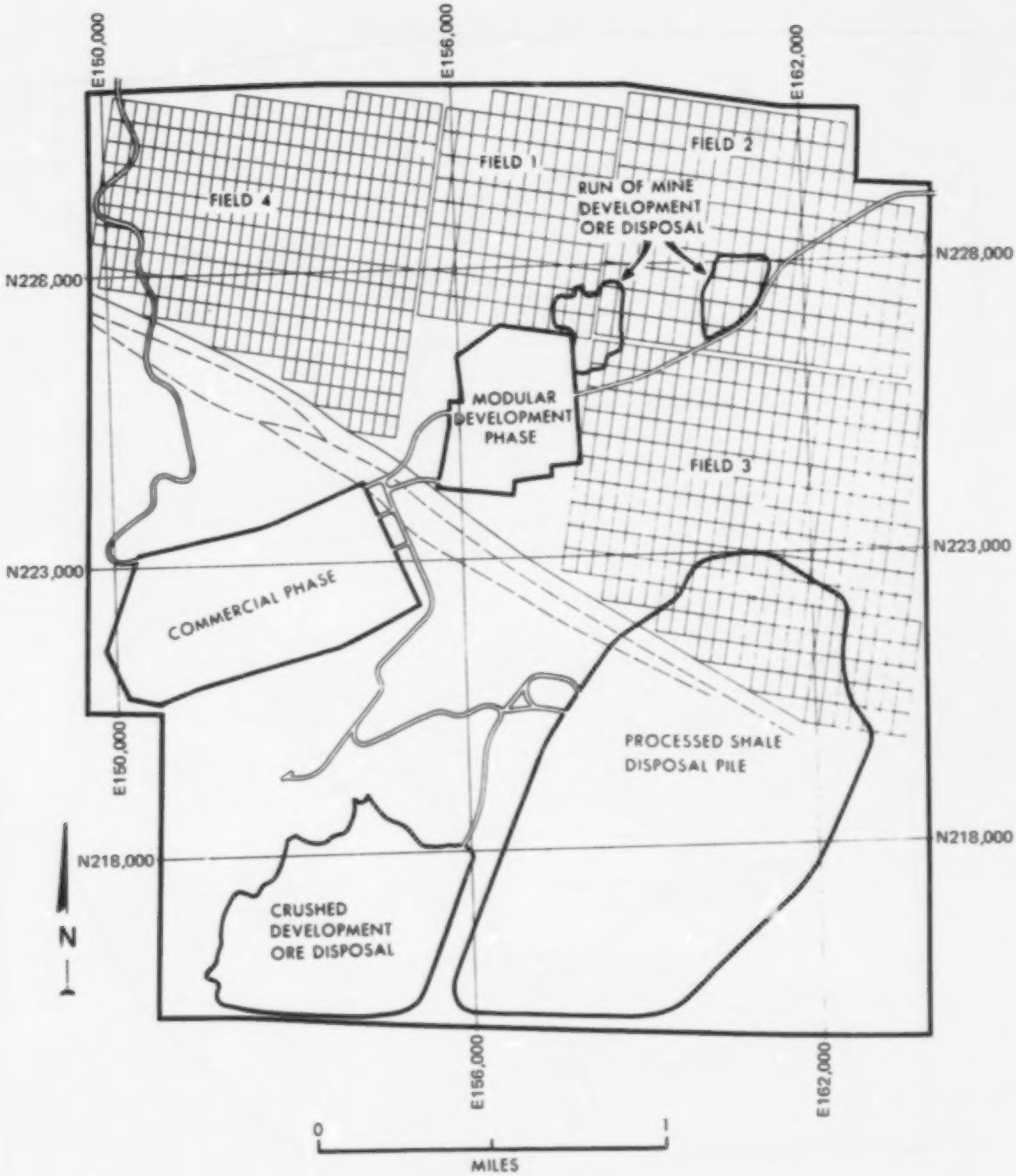
E150,000
E156,000
E162,000
FIELD 4
FIELD 1
FIELD 2
RUN OF MINE DEVELOPMENT ORE DISPOSAL
N228,000
N228,000
MODULAR DEVELOPMENT PHASE
FIELD 3
N223,000
N223,000
COMMERCIAL PHASE
PROCESSED SHALE DISPOSAL PILE
E150,000
N218,000
N218,000
CRUSHED DEVELOPMENT ORE DISPOSAL
N
E156,000
E162,000
0
1
MILES

Figure 2-3. General location map of Tract C-a facilities (RBOSP, 1977a).

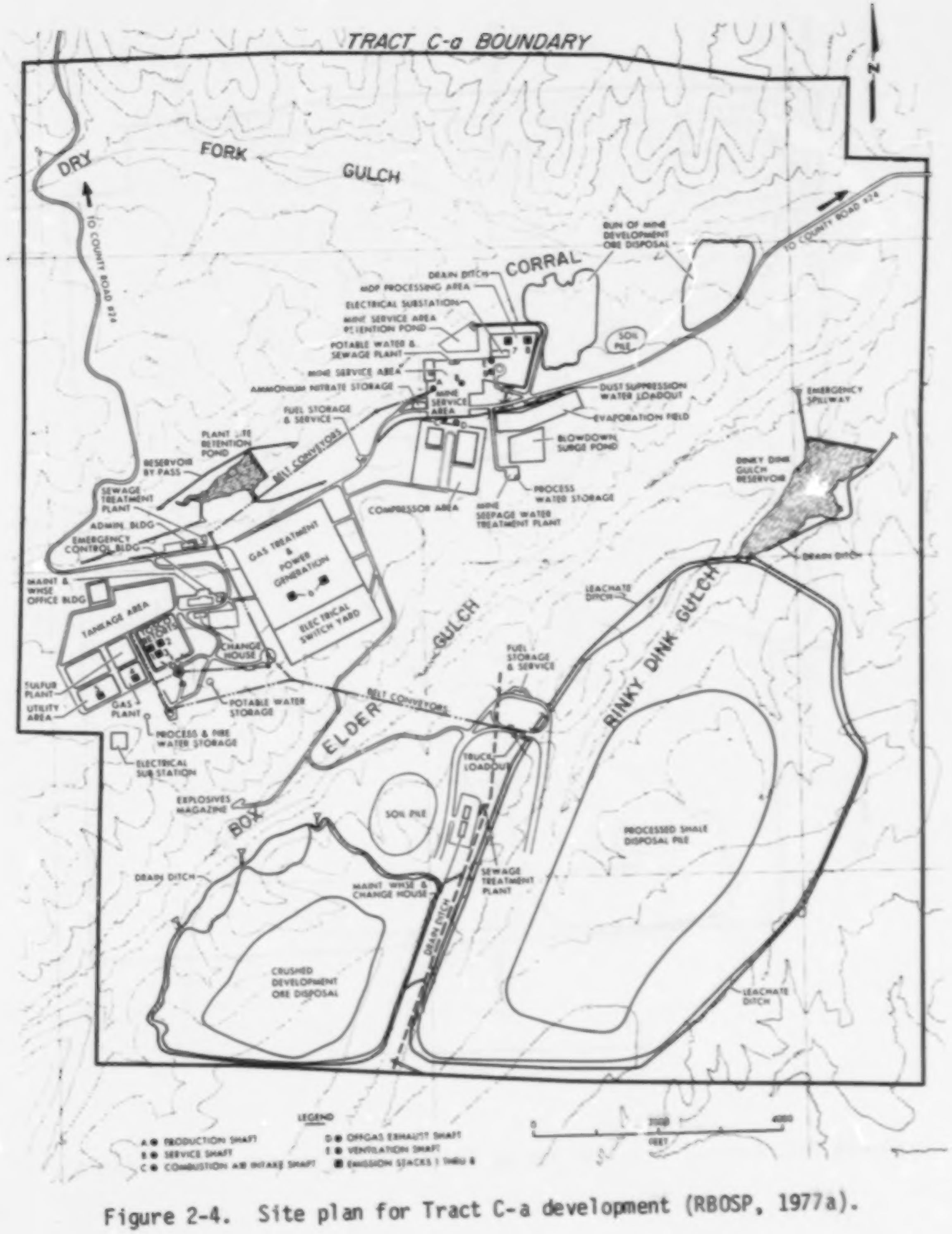
TRACT C-a BOUNDARY
N
DRY
FORK
GULCH
TO COUNTY ROAD #24
TO COUNTY ROAD #24
CORRAL
RUN OF MINE DEVELOPMENT ORE DISPOSAL
DRAIN DITCH
MDP PROCESSING AREA
ELECTRICAL SUBSTATION
MINE SERVICE AREA RETENTION POND
POTABLE WATER & SEWAGE PLANT
MINE SERVICE AREA
AMMONIUM NITRATE STORAGE
MINE SERVICE AREA
FUEL STORAGE & SERVICE
SOIL PILE
DUST SUPPRESSION WATER LOADOUT
EVAPORATION FIELD
BLOWDOWN SURGE POND
PROCESS WATER STORAGE
MINE SEEPAGE WATER TREATMENT PLANT
COMPRESSOR AREA
EMERGENCY SPILLWAY
BINKY DINK GULCH RESERVOIR
DRAIN DITCH
PLANT SITE RETENTION POND
RESERVOIR BY PASS
BELT CONVEYORS
SEWAGE TREATMENT PLANT
ADMIN. BLDG
EMERGENCY CONTROL BLDG
MAINT & WHSE OFFICE BLDG
TANKAGE AREA
GAS TREATMENT & POWER GENERATION
ELECTRICAL SWITCH YARD
CHANGE HOUSE
SULFUR PLANT
UTILITY AREA
GAS PLANT
POTABLE WATER STORAGE
PROCESS & FIRE WATER STORAGE
ELECTRICAL SUB STATION
EXPLOSIVES MAGAZINE
BOX
ELDER
GULCH
BELT CONVEYORS
LEACHATE DITCH
FUEL STORAGE & SERVICE
BINKY DINK GULCH
TRUCK LOADOUT
SOIL PILE
SEWAGE TREATMENT PLANT
MAINT. WHSE & CHANGE HOUSE
DRAIN DITCH
DRAIN DITCH
CRUSHED DEVELOPMENT ORE DISPOSAL
PROCESSED SHALE DISPOSAL PILE
LEACHATE DITCH
LEGEND
A ● PRODUCTION SHAFT
B ● SERVICE SHAFT
C ● COMBUSTION AIR INTAKE SHAFT
D ● OFFGAS EXHAUST SHAFT
E ● VENTILATION SHAFT
■ EMISSION STACKS 1 THRU 8
0
2000
4000
FEET

Figure 2-4. Site plan for Tract C-a development (RBOSP, 1977a).

retorts against leaching by groundwater, and (3) disposal of the processed shale.

Processing, operation support, and other surface facilities include:

- Surface retorts
- Shale oil processing facilities
- Water treatment for mine seepage, potable water, and sewage
- Various water storage and retention basins for runoff, potable water, process water, and blowdown water
- Gas treatment facilities
- Electric power generation
- Tankage for products, fuel, oil additives, etc.
- Storage for explosives and other materials
- Surface retorts
- Sulfur storage.

Mine dewatering during the modular development and commercial phases will produce more water than is required for project needs. This excess water will be reinjected. Up to 100 acre-feet per year of groundwater will be used during the modular development phase, obtained from mine seepage and/or the dewatering wells. During the commercial phase, approximately 2200 acre-feet per year of groundwater will be used.

Product shale oil will initially be transported by truck and later by pipeline. Product sulfur will be transported from the tract by truck.

Potential Pollution Sources

A number of components of MIS development such as proposed on Tracts C-a and C-b have some potential for impact on groundwater quality. The following identifies the elements of mining, in-situ retorting, surface retorting, and other surface processing which have such a potential.

Mining--

Included under the heading of mining operations are those activities related to the development of access to in-situ retorts, development of the in-situ retorts including excavation and rubbling, and dewatering operations.

Mine access development--During the MDP, mine access tunnels and ventilation and service-production shafts will be developed. These operations are outlined as follows:

	Dimensions
Sublevel tunnels	Either 15- x 12- or 13- x 10-foot cross sections
Ventilation shaft	7-foot diameter, 1185 feet deep
Service-production shaft	15-foot diameter, 1185 feet deep

Similar operations, but on a larger scale, will be included in the commercial phase of development:

	Dimensions
Sublevel tunnels	25- x 17-foot cross sections
Ventilation shafts	Two shafts, 34 feet in diameter; combustion air shaft, 16 feet in diameter
Service-production shaft	One shaft, 34 feet in diameter; one shaft, 24 feet in diameter

The materials excavated during mine access development will be disposed of on the surface. MDP wastes will be deposited near the modular development area where they will be contoured, covered with soil, and revegetated. Materials generated by commercial mine development will probably be treated in a similar manner.

Retort development--As previously noted, approximately 20 percent of the retort zone will be excavated during retort development to produce suitable porosity within the retort. These activities for the original MDP program are summarized as follows:

Development phase	Material brought to surface (average TPD)
Modular	
Retorts 1-5	500
Retorts 6 and up	3,000
Commercial	40,000

Excavated materials brought to the surface during the MDP will be disposed of at the surface as described above. These oil shale materials will be crushed and retorted at the surface once commercial feasibility is proven. During the MDP, up to 12,000 tons per day will be rubblized in situ for retorting. Commercial-scale operations will include in-situ rubblizing of 134,000 tons per day.

Beyond surface disposal sites, potential in-situ sources of groundwater quality impact result from the fracturing within and extending from the retort zone. This potential influence of restructuring of the area hydrogeology will not manifest itself during mine development nor retorting due to dewatering of the operating zone. The effects of such fracturing and restructuring may be very significant after retort abandonment and termination of dewatering.

Dewatering--Mine development, in-situ retort development, and actual retorting will require dewatering of the operating zone. A dewatering/injection well program is being developed to support present MDP operations. In addition, water will be collected within the mine in sumps. This water will be reinjected, stored, and used for dust control or other purposes, or released to surface streams.

In-Situ Retorting--

During retorting, in-situ retorts themselves probably do not pose a great threat to groundwater systems. This is because dewatering operations will hydrologically isolate the retorting zone and temperatures within the retort will preclude the presence of liquid water. However, the products of in-situ retorting which may remain in the subsurface are appreciable potential pollution sources after abandonment. Items of importance in this regard include:

- Escape of retort gases, shale oil products and retort water into the aquifer zones around the retort (Tract C-b developers have indicated that retorts will be kept under negative pressure until cooled below 212°F to avoid this problem)
- Residual materials (gases, shale oil, retort water, spent shale) remaining in the retort after completion of the production burn
- Release of shale oil or retort water during transport within the mine
- Expansion of fractures (natural or created during rubbling of the retort) during retorting by temperature or pressure stresses, or due to subsidence or related failure of the retort walls.

The mass of material (i.e., potential pollutants) associated with this source is unclear. Oil, gas, and retort water are to be brought to the surface to be treated and transported or disposed.

As indicated above, MIS retorting becomes a significant potential pollution source after abandonment of the in-situ retorts. Eventually, dewatering of the retort zone will be terminated, allowing recovery of water levels in the aquifers adjacent to the retort zone. Interconnection of abandoned in-situ retorts and the adjacent aquifer system is not a certain event, but it is a highly likely event. Water entering abandoned retorts may result in the following:

- Aquifer interconnection through retorts and mine tunnels and shafts
- Leaching of inorganic and organic materials remaining in the retort
- Possible further restructuring of the hydrogeologic system due to the effects of water saturation on the structural integrity of spent shale and retort walls.

The amount of spent shale in spent retorts is as follows:

Development phase	Retort	Dimension (feet)	Mass of spent shale (10^4 tons)*
Modular	1, 2	30 x 30 x 140	0.8 - 1.14
	3, 4	50 x 50 x 140	2.2 - 3.3
	5	100 x 150 x 400	18.7 - 27.3
	6	150 x 300 x 700	98.1 - 144.0
Commercial	--	150 x 300 x 750	105.0 - 154.0†

Surface Retorting--

Eventual commercial-scale operations on Tract C-a include surface retorting of oil shale mined during development of in-situ retorts. Potential pollution sources associated with surface retorting include:

- Raw shale stockpile (100,000 tons)
- Retort water
- Processed shale.

Raw shale will be stored only temporarily prior to retorting. However, some potential exists for leaching of soluble materials during storage. Development plans call for evaporation/combustion of retort waters using a thermal oxidizer.

Processed shale will be disposed of at the surface and will be revegetated. One alternative currently being studied is the injection of slurried processed shale into abandoned in-situ retorts to aid in sealing and stabilizing. If slurry injection is not feasible, spent shale from the surface retorts will be transported via conveyor belt to the disposal area where it will be spread and compacted. The spent shale, moisturized to about 15 percent (by weight) is expected to have a compacted density of 85 pounds per cubic foot. The total compacted volume will be 310 million cubic yards.

---

* Range of estimates listed result from range of bulk density data used. A bulk density of 1 gm/cc for in-situ spent shale from Amy (1978) is a lower end of range. Margheim (1975) indicates an in-place rock density of 2.3 gm/cc. Removal of 20 percent of mass before rubblizing and another 20 percent during retorting yields a bulk density of 1.46 gm/cc. This value was used for the upper range estimate.

† 932 retorts, over a 30-year development, yield approximately 9.8 to 14.4 x 10^8 tons of in-situ spent shale.

Surface Processing--

Surface processing (Figure 2-5) includes the following elements:

- Raw water treatment
- Retort water treating (oil-water separation and foul water stripping)
- Power and steam generation
- Oil treatment and upgrading
- Gas treatment
- Waste water (sewage) treatment
- Tankage.

Raw water treatment (Figure 2-6) will include hot lime and hot zeolite softening. Lime sludge wastes (870 tons per year) will be dewatered using the thermal oxidizer and subsequently deposited in solid waste landfills in the processed shale pile. Regenerant brines from the hot zeolite process will be transported to a blowdown sludge pond. Spent zeolites (3 tons per year) will also be deposited in spent shale pile landfills.

Retort water will be separated from shale oil product utilizing an API separator (skimming) system (Figures 2-5 and 2-6). Oily waste water from the API system will be discharged to the process area retention pond and subsequently used for dust control. Other retort waters from the oil recovery and retort-gas condensate will be treated in the foul water stripper, with distillate going to steam generation, and stripped water will be used for shale moisturizing.

Power generation and other process equipment will require cooling water which will be obtained from mine seepage and the potable water treatment systems. Blowdown from cooling water and boiler systems will be discharged to the blowdown surge pond and subsequently evaporated (Figure 2-6).

After retorting product fractionation (into water, gas, and oil), the oil will be fractionated into naphtha and heavy oil fractions. The gas will be compressed, treated for sulfur removal, and used as a fuel to produce electric power. Heavy oil will be treated as required with flow-improving chemicals and blended with naphtha and C_4 fractions to produce pipeline-quality oil (Figure 2-5).

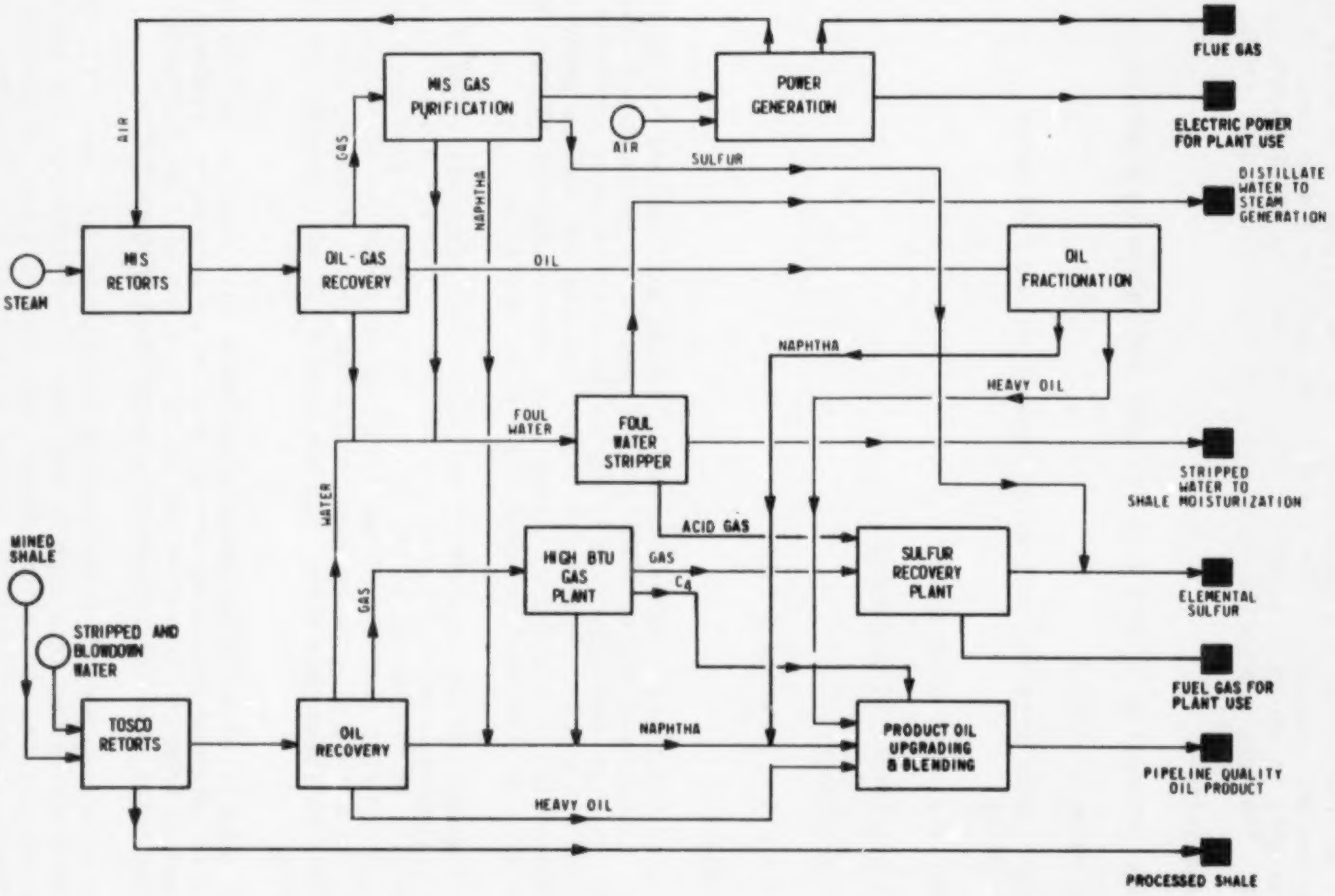
STEAM
MIS RETORTS
AIR
OIL-GAS RECOVERY
GAS
MIS GAS PURIFICATION
NAPHTHA
AIR
POWER GENERATION
SULFUR
OIL
OIL FRACTIONATION
NAPHTHA
HEAVY OIL
FOUL WATER
FOUL WATER STRIPPER
ACID GAS
WATER
MINED SHALE
STRIPPED AND BLOWDOWN WATER
TOSCO RETORTS
OIL RECOVERY
GAS
HIGH BTU GAS PLANT
GAS
C_4
SULFUR RECOVERY PLANT
NAPHTHA
PRODUCT OIL UPGRADING & BLENDING
HEAVY OIL
FLUE GAS
ELECTRIC POWER FOR PLANT USE
DISTILLATE WATER TO STEAM GENERATION
STRIPPED WATER TO SHALE MOISTURIZATION
ELEMENTAL SULFUR
FUEL GAS FOR PLANT USE
PIPELINE QUALITY OIL PRODUCT
PROCESSED SHALE

Figure 2-5. Flow diagram of commercial phase processing facility (RBOSP, 1977a).

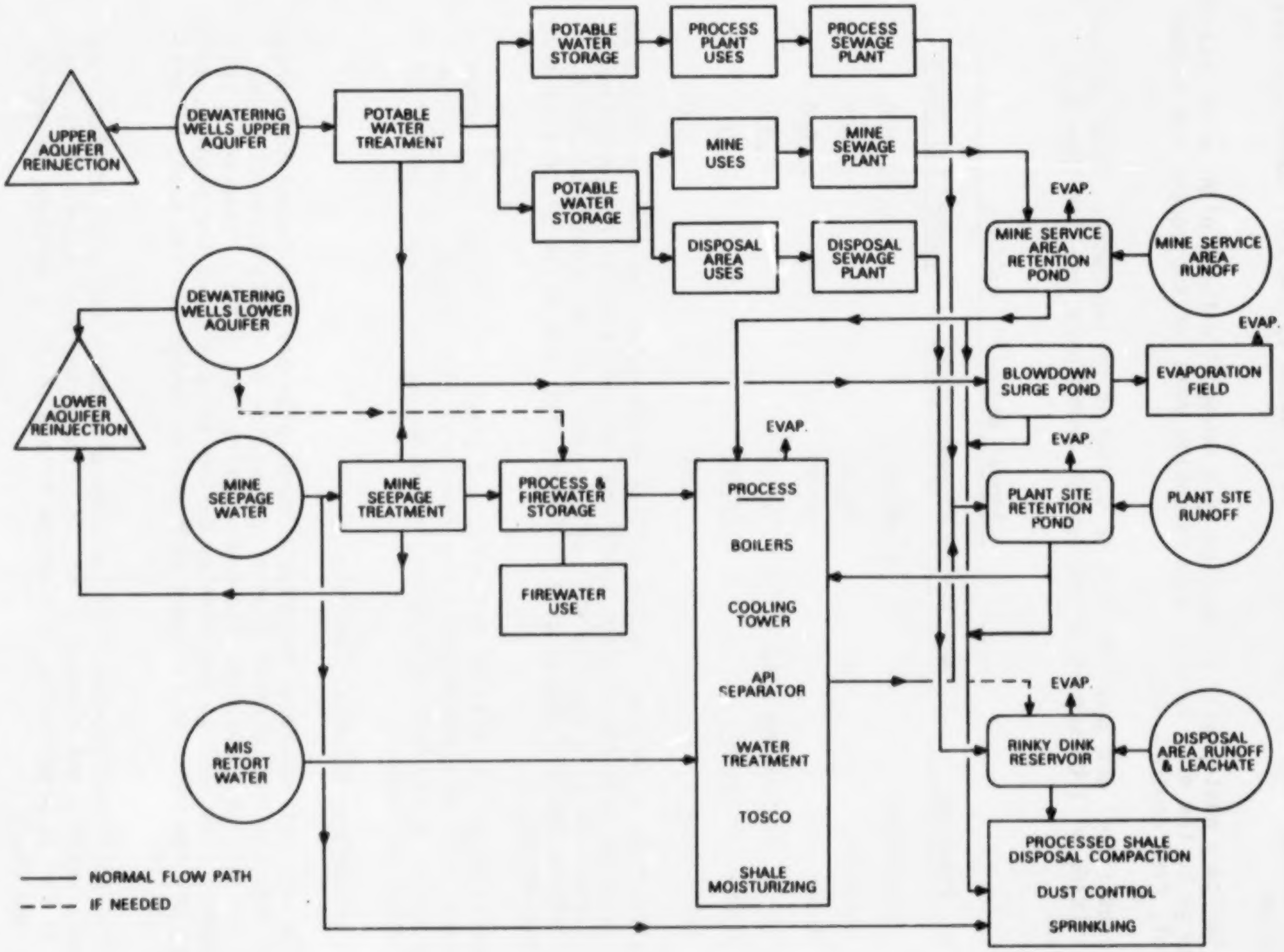
UPPER AQUIFER REINJECTION
DEWATERING WELLS UPPER AQUIFER
POTABLE WATER TREATMENT
POTABLE WATER STORAGE
PROCESS PLANT USES
PROCESS SEWAGE PLANT
POTABLE WATER STORAGE
MINE USES
MINE SEWAGE PLANT
DISPOSAL AREA USES
DISPOSAL SEWAGE PLANT
EVAP.
MINE SERVICE AREA RETENTION POND
MINE SERVICE AREA RUNOFF
DEWATERING WELLS LOWER AQUIFER
LOWER AQUIFER REINJECTION
EVAP.
BLOWDOWN SURGE POND
EVAPORATION FIELD
MINE SEEPAGE WATER
MINE SEEPAGE TREATMENT
PROCESS & FIREWATER STORAGE
FIREWATER USE
EVAP.
PROCESS
BOILERS
COOLING TOWER
API SEPARATOR
WATER TREATMENT
TOSCO
SHALE MOISTURIZING
EVAP.
PLANT SITE RETENTION POND
PLANT SITE RUNOFF
EVAP.
RINKY DINK RESERVOIR
DISPOSAL AREA RUNOFF & LEACHATE
MIS RETORT WATER
PROCESSED SHALE DISPOSAL COMPACTION
DUST CONTROL
SPRINKLING
NORMAL FLOW PATH
IF NEEDED

Figure 2-6. Water flow schematic for Tract C-a development (RBOSP, 1977a).

The byproduct of gas treatment and the TOSCO process is elemental sulfur. A total of 265 long tons per day will be produced by the full commercial-scale operation.

Sanitary wastes will be handled by a sewage treatment plant with treated discharge to the mine service area retention pond for subsequent use in dust control, fire control, etc.

Diesel fuel and gasoline will be stored in buried tanks. Motor oil and other fluids will be stored in the durable containers in which they are shipped.

	Annual amount in gallons	
Products	Modular development phase	Commercial phase
Diesel fuel	1,055,000	5,900,000
Gasoline	46,000	135,000
Motor oil	15,000	45,000
Other lubricating oils	1,500	5,000
Hydraulic fluid	18,000	52,000
Antifreeze	200	500

During the MDP, a service station will be provided at the mine service area in conjunction with the storage tanks and delivery facilities. Additional service stations with tankage will be provided for the commercial phase at the processed shale disposal area equipment shop and at the processing area maintenance shop.

Waste motor oil will be collected and mixed with diesel fuel. Used antifreeze will be discharged to the sanitary sewer system. Sludge from diesel tanks, waste hydraulic fluid, and other waste oils will be burned in the thermal oxidizer.

Oil and Hazardous Material Control--

The oil and hazardous material control plan has been formulated recognizing that the best control plan is prevention of spills through proper design of storage, handling, and transporting facilities. However, a spill contingency plan will be implemented during all phases of the project, establishing procedures to be followed to minimize damages in the event of accidental spills.

This spill contingency plan includes procedures for notification, containment, repair, and cleanup of spills. The primary objective is to minimize, as far as practicable, any damage from a spill to persons, property, flora, and fauna.

The layout and construction of tanks, valves, piping, and appurtenances will be designed to minimize the possibility of spillage. Tanks will be enclosed by dikes designed to form spill-containment basins. The drainage from these diked areas will enter the processing facility storm drainage system and pass through an API oil separator. Catchments will be constructed in any natural drainages immediately downhill from the oil storage facilities so that should any oil find its way outside containment facilities, it can be easily controlled before it reaches a water course.

Contingency plans for the MIS underground oil/water pumproom will cover design (grading, emergency equipment and facilities, control and warning systems, etc.), operating guidelines, and spill response guidelines.

A detailed spill contingency plan will be developed for both nontransportation- and transportation-related facilities. This plan will include procedures to be followed in the event of a spill detection and will include procedures for system shutdown, notification, reporting to Federal and State agencies, internal reporting, containment of the spill, removal of spilled material, and cleanup and restoration of the contaminated site.

Land Rehabilitation and Erosion Control--

The objectives of the land rehabilitation program are to reclaim disturbed areas by returning them to a state that does not contribute to environmental deterioration and is consistent with surrounding aesthetic values. The overall concept of rehabilitation efforts for the project includes numerous problems and considerations dealing with mining access, plant sites, parking lots, conveyor corridors, access roads, pipelines, etc. The principal elements considered are site preparation, erosion control, and revegetation.

Table 2-2 shows estimates of the yearly disturbed surface areas and areas ready for rehabilitation for the operation. The Rangely access road, power line, and telephone line are excluded because they will be constructed and rehabilitated by other entities, i.e., Rio Blanco County, Moon Lake Electric, and Mountain Bell.

Site preparation, or the shaping and grading of areas being rehabilitated, is controlled by three primary environmental concerns: erosion control, aesthetics, and the plant species to be supported. One additional factor influencing the rehabilitation work is the method selected for constructing an artificial soil profile on the processed shale disposal pile to facilitate revegetation.

Surface runoff will be controlled throughout the project area. Diversions around the mine, processing facility, and processed shale disposal pile will be provided. Surface water originating outside the project area will be diverted completely around RBOSP facilities and returned to an existing water course downstream. Surface runoff originating within the RBOSP area will be controlled and will not be released to downstream water courses unless its quality is shown to be adequate.

TABLE 2-2. ESTIMATED ACREAGES OF LAND SCHEDULED TO BE DISTURBED AND REVEGETATED ON TRACT C-a (RBOSP, 1977a)

Disturbed:	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987-1991	1992-1996	1997-2001	2002-2006	2007-2011	2012-2016	Total
Mine and plant sites	34				26	218										278
Run of mine disposal area	65															65
Crushed ore disposal							130	130								260
Corridors	100	12			21	39				104						276
Processed shale disposal pile									70	320	210	40	240			880
	199	12			47	257	130	130	70	424	210	40	240			1759
Reclaimed:																
Run of mine disposal area						15	20	30								65
Crushed ore disposal									200						60	260
Corridors		80	12			21	32			104						249
Processed shale disposal pile											20	215	215	215	215	880
		80	12			36	52	30	200	104	20	215	215	215	275	1454

Water Supply and Demand--

Water supply--The water supply for development of Tract C-a will come from mine dewatering systems, water produced by the MIS retorting operation, and surface drainage water.

As now planned, the MDP mine dewatering system will consist of separate wells for the Upper and Lower Aquifers and mine seepage. Dewatering during this phase will vary widely but should always be in excess of requirements. The project water requirements from dewatering systems will be approximately 1000 acre-feet per year.

The mine dewatering system will be continually modified with the addition of new wells and abandonment of old ones as the underground mine area grows throughout the commercial phase operations. Mine dewatering is expected to produce about 18,000 acre-feet per year. Water requirements from dewatering systems will be approximately 2200 acre-feet per year. Excess water produced from dewatering well and mine seepage will be reinjected to reduce the overall effect on the groundwater aquifers.

Water demand--Estimated water usages (in gallons per minute) for the modular development and commercial phases are shown as follows:

Use	Modular development phase	Commercial phase
Processing*	710	2,200
Potable	35	60
Dust control and miscelleanous	220	1,250
Total	965	3,530

Processing uses include water for boiler feed, cooling, moisturizing processed shale, operation of retort scrubbers, disposal of MIS retort water, and miscellaneous uses.

DEVELOPMENT SUMMARY--TRACT C-b

Project Description

The development of the commercial MIS facilities is shown on the project plot plan (Figure 2-7). The Tract C-b development program will extend from September 1, 1977, starting with site preparation, to September 1982, when the mine and surface facilities will be capable of full-scale production.

The property will be mined by developing successive geographic areas called panels. A commercial panel will consist of 32 clusters with 8 retorts

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* Does not include water of combustion.

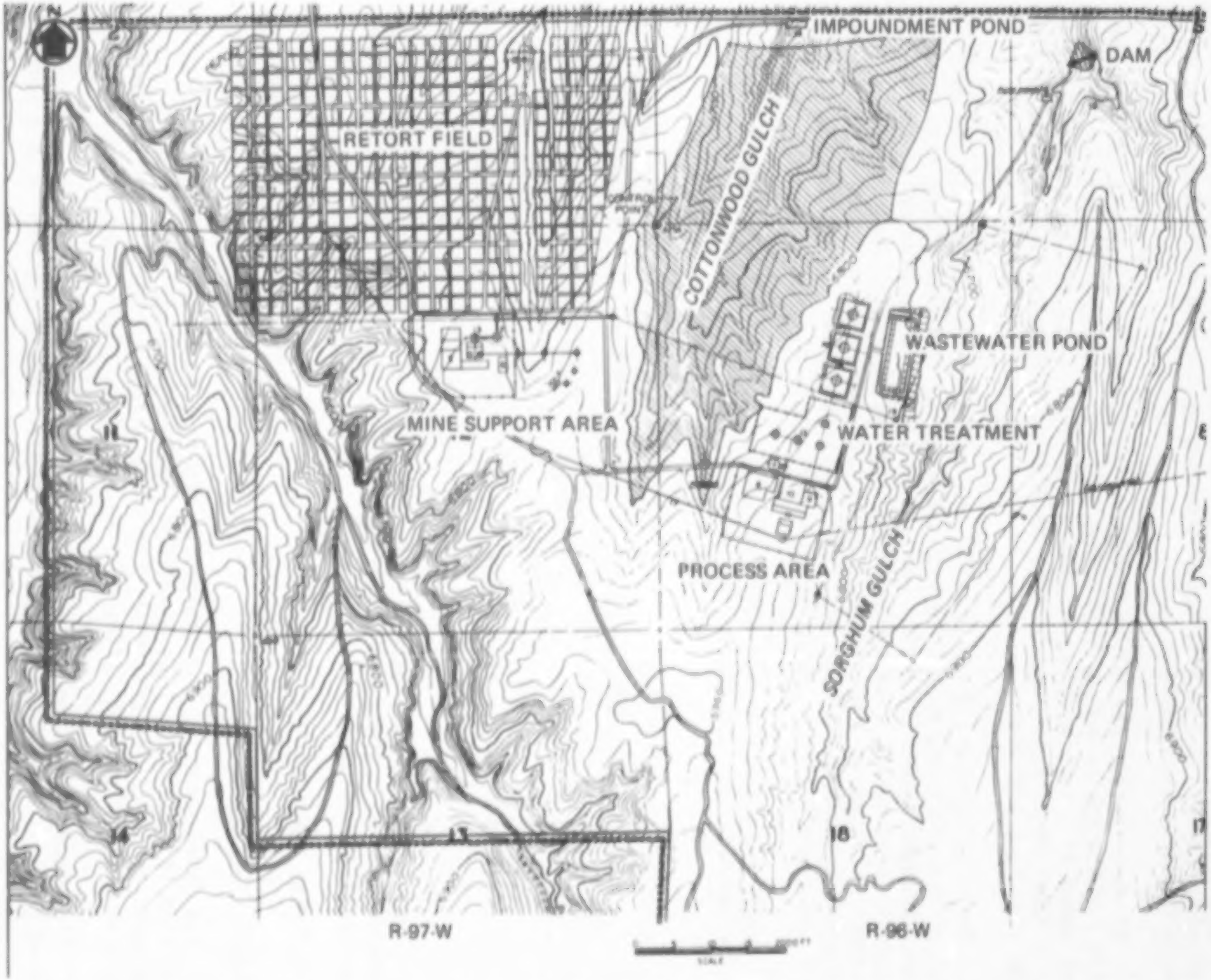

IMPOUNDMENT POND
DAM
RETORT FIELD
COTTONWOOD GULCH
WASTEWATER POND
MINE SUPPORT AREA
WATER TREATMENT
PROCESS AREA
SORGHUM GULCH
R-97-W
R-96-W

Figure 2-7. Plot plan for Tract C-b development (from C-b Oil Shale Venture, 1977a).

per cluster. At a production rate of 57,000 barrels per day, a commercial panel will take 4 years to develop completely. An equivalent of 15 panels is proposed for Tract C-b totaling 3840 individual retorts with dimensions of 200 x 200 x 310 feet. Forty retorts will operate simultaneously during full commercial production.

Using the range of bulk density of 1.0 to 1.46 gm/cc for spent shale, this commercial operation is estimated to produce from 1.5 to 2.2 x 10^9 tons of in-situ spent shale.

Site Preparation and Shaft Sinking--

The first site activities starting in September 1977 will be shaft sinking for mine access. At the same time, certain site preparation and preconstruction activities will proceed, including preparation or extension of service roads, construction of water storage to receive underground water from initial dewatering operations, and necessary grading for temporary construction facilities, fencing, etc.

Full-Scale Modified In-Situ Plant and Operations--

The construction period of the full-scale commercial facility will begin with shaft sinking in September 1977 and end September 1982 when the first cluster within the commercial panel is kindled. The construction of the major oil/gas processing units and general facilities will occur between January 1981 and September 1982. As more clusters are brought on-line, production will increase and full-capacity production (57,000 barrels per day) will be achieved in about 12 months, or by September 1983 (Figure 2-7). Operations will continue from September 1982 to about the year 2040, when the resource interval will be exhausted.

An ancillary development site located near the north-central border of Tract C-b had initially been proposed. This facility was to include two or more commercial-sized retorts, retort clusters, and associated operating equipment. This development was proposed to establish environmental monitoring procedures, obtain operating experience, and provide for training of personnel. Tract development plans now include initial retorting operations within the commercial mine complex described above and illustrated in Figure 2-7.

Potential Pollution Sources

The basic nature of the MIS development operations proposed for Tract C-b is the same as that described above for Tract C-a. The major differences are the Tract C-a MDP and the surface retorting of mined oil shale, which have no present counterpart in Tract C-b.

Hence, potential sources of groundwater quality impact identified for Tract C-a MIS development are also characteristic of Tract C-b development plans. Some differences do exist with regard to the mass of materials involved. The following is a brief description of the retorting process (C-b Oil Shale Venture, 1977a).

The processing of a cluster of retorts consists of several steps. First, a retort within a cluster is kindled from the top by externally fueled burners. When the temperature at the top of the retort is sufficient to sustain reaction, the burners are shut off and a regulated mixture of air and steam is drawn into and through the retort by exhaust blowers on the surface. Residual organic material is combusted with the air in the feed gas. The hot combustion gases flow down through the retort and supply heat to the raw, unretorted shale below. As the shale is heated, the organic material, or kerogen, decomposes into oil vapor and other gases that are carried along with the combustion gases, while some residual organic material remains in the rubble. Steam in the feed gas acts as a diluent to the oxygen in the air to control the reaction temperature and reacts with some of the residual organic material, forming carbon monoxide and hydrogen to improve the heating value of the product gas. Some of the mineral carbonates in the shale are also decomposed to carbon dioxide gas and mineral oxides. As the gas mixture flows down through the retort, it preheats the raw shale. At the same time, the oil and some of the water vapor are condensed. Product liquids and gas leave the bottom of the retort and move to the surface for further processing as product oil, fuel gas, and water.

As the retorting progresses, the combustion and retorting zones move slowly down through the in-situ retort. Between 7 and 8 months are required to process a cluster. When retorting is complete, the air and steam feed are stopped and the in-situ retort is closed off. The spent shale remains underground with no need for surface disposal.

Surface process facilities consist only of oil/water separation equipment, exhaust blowers, a sulfur removal unit for treatment of product gas, and boilers to produce process steam from the product gas.

A block diagram of the C-b commercial phase operation is shown in Figure 2-8. Details not available on development plans include the characteristics of treatment and disposal and sizing for the following:

- Retort water

- Oil treatment or upgrading on site

- Tankage on site.

Water Supply and Demand--

It is anticipated that water available from the mine will be more than required by the C-b operation during early stages of development, but slightly less than required for full commercial operations:

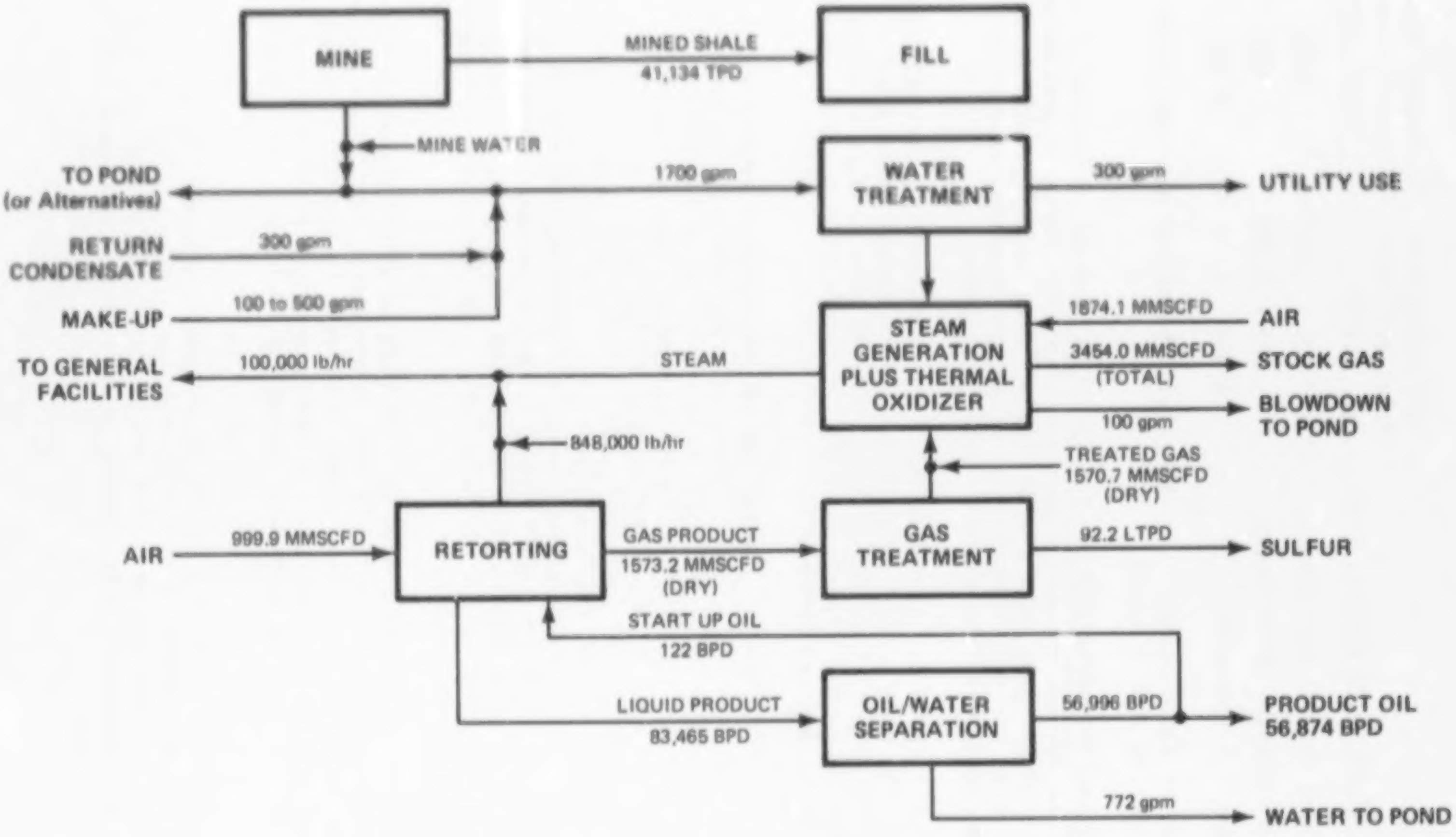

MINE
MINED SHALE
41,134 TPD
FILL
MINE WATER
TO POND
(or Alternatives)
1700 gpm
WATER TREATMENT
300 gpm
UTILITY USE
RETURN CONDENSATE
300 gpm
MAKE-UP
100 to 500 gpm
TO GENERAL FACILITIES
100,000 lb/hr
STEAM
STEAM GENERATION PLUS THERMAL OXIDIZER
1874.1 MMSCFD
AIR
3454.0 MMSCFD
(TOTAL)
STOCK GAS
100 gpm
BLOWDOWN TO POND
848,000 lb/hr
TREATED GAS
1570.7 MMSCFD
(DRY)
AIR
999.9 MMSCFD
RETORTING
GAS PRODUCT
1573.2 MMSCFD
(DRY)
GAS TREATMENT
92.2 LTPD
SULFUR
START UP OIL
122 BPD
LIQUID PRODUCT
83,465 BPD
OIL/WATER SEPARATION
56,996 BPD
PRODUCT OIL
56,874 BPD
772 gpm
WATER TO POND

Figure 2-8. Flow diagram for Tract C-b commercial operations (C-b Oil Shale Venture, 1977a).

Status of mine and process plant	Estimated mine water available (gpm)	Estimated mine and process water usage (gpm)
Initial retort development	400 - 1,000	310
Retort cluster development	800 - 2,000	460
Commercial operation	2,000 - X	2,500

If a surplus of water occurs, the excess will be stored and then either reinjected or treated and released.

During shaft-sinking and the initial retort period, a surplus of water of from 100 to 700 gallons per minute is anticipated based on preliminary hydrologic studies. This water, depending on final quantity, will be either stored for later use or disposed of by evapotranspiration, reinjection into aquifers, or treated and released to surface streams.

An existing pond in Cottonwood Gulch (see Figure 2-7) will provide initial storage for water during development. A temporary impoundment north of the Cottonwood pond at the edge of the tract can also be used to store water, if necessary, until the Sorghum Gulch Dam is constructed or other options, as discussed above, are exercised.

During the first retort cluster period, anticipated water surplus over requirements (see Figure 2-8) will be from 500 to 1500 gallons per minute. Surface storage volume will increase as construction of the Sorghum Gulch Dam (Figure 2-7) and the gas treatment area impoundment pond are completed. The Sorghum Gulch Dam will be of earthfill construction and constructed to a height of approximately 80 feet. The dam will enable productive use of the rock excavated during surface facility and mine shaft construction, and will provide a water containment system for storm runoff from the construction area and serve as a storage system for groundwater produced from shaft-sinking and development mining activities. The impoundment will have a maximum capacity of approximately 600 acre-feet. The dam site will require approximately 6 acres of land.

A coronation diversion system will be used to divert rainwater around the shale disposal area and into the dam impoundment. Additional catchment ponds may be installed above the Sorghum Reservoir to capture sediment from the shale and prevent it from reaching the reservoir. Water from the catchment ponds will be used to supplement needs for shale dust and compaction control.

It may be found necessary to retain and make permanent the Cottonwood Gulch temporary impoundment pond constructed earlier to collect runoff from the plant area drainage system. This water, depending on quality, would either join the Sorghum Reservoir water or be added to the lower-quality water for shale use.

The lined pond adjacent to the gas treatment area would revert from general water storage use to its final service as containment settling and concentration area for product water and process blowdowns.

Land Disturbance--

Estimates of land disturbance due to Tract C-b development and operation are summarized in Table 2-3.

TABLE 2-3. ESTIMATED SURFACE DISTURBANCE BY YEAR AND OVERALL (acres)

Activity	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11 to Year 2005	Total by activity
Mine development:												
Surface facilities (15-ft shaft)		8										8
Steam generation		3										3
Gas treatment		3										3
Cottonwood Gulch:												
Mined rock fill area		15	20	75	100	100						310
Impound pond			4									4
Road construction:												
Tract access		8	20	25								53
Service		3	5									8
In situ gas treatment facilities			44	30								74
Mine production and service shaft area			15	15								30
Sorghum Gulch:												
Dam site			3									3
Reservoir			3	17								20
Shale storage area							100	100	100	100	540	940
Total by year (accuracy of estimate ±25 percent)		40	114	162	100	100	100	100	100	100	540	1,456

SECTION 3

POTENTIAL POLLUTANTS

In the preceding section, potential sources of groundwater quality impact were identified. The potential pollutants associated with these various sources are the subject of this section. This discussion focuses on modified in-situ retorts. Consideration of surface operations may be found in the initial project report dealing with the Utah Federal Lease Tracts U-a and U-b (Slawson, 1979).

RETORT WATER

The major potential pollution sources associated with in-situ retorts are the retort water and the in-situ spent shale. Available data related to characterizing these sources are presented in the following discussion.

Retort or process waters from in-situ retorts will be for the most part brought to the surface with other liquid products to be treated, used, or disposed. In addition, it may be expected that some of these waste waters will remain in the spent retorts. Retort waters are of particular importance as potential pollutant sources because the volume produced is expected to be roughly equivalent to the volume of shale oil produced. The origin of these process waters is combustion in the retort, dehydration of minerals, and local groundwater. Thus, the exact composition will be site specific and variable. These waters are described as brown to yellow in color with alkaline pH and high levels of inorganics and organics. Major inorganics include bicarbonates, carbonates, fluoride, magnesium, sodium, sulfate, and ammonia. Organics are dominated by polar (e.g., carboxylic acids) consituents.

Table 3-1 lists the results of analysis of waters from several different simulated in-situ retorts. The reported data are from several simulation experiments (performed in aboveground vessels of laboratory or pilot scale) and the analyses were performed by several different laboratories. Also presented are the results of a single sample from an MIS retort developed by Occidental Oil Shale, Inc.

Table 3-2 lists the results of analysis of retort water obtained from true in-situ tests at Rock Springs, Wyoming. Although this retorting approach is different from MIS retorting, the combustion character of both processes is similar and thus results should be applicable to MIS development. Again, data from MIS retort no. 6 at Logan Wash are provided here for comparison. General agreement can be seen with regard to levels of total dissolved solids, sodium, potassium, organic carbon, organic nitrogen, and many trace metals.

TABLE 3-1. CHEMICAL CHARACTERIZATION OF SIMULATED AND OBSERVED IN-SITU OIL SHALE PROCESS WATER

Constituent	Concentration (mg/l)[a]			
	Minimum	Maximum	Median[b]	Retort no. 6[c]
General water quality measures				
Total alkalinity ($CaCO_3$)	18,200	110,900	---	540
Conductivity (μmhos/cm)	15,100	193,000	31,000	---
Hardness ($CaCO_3$)	20	1,500	88	---
pH (pH units)	8.1	9.4	8.7	---
Solids, dissolved	1,750	24,500	6,800	13,000
Solids, total	6,350	121,000	---	13,000
Major inorganics				
Bicarbonate	4,200	73,640	---	659
Carbonate	0	15,210	---	<1
Chloride	0.007	1,910	---	240
Fluoride	0.1	270	---	15
Sulfate	42	2,200	1,400	4,000
Sulfide	0	156	---	---
Ammonia-N	1,700	13,200	7,000	3.1
Ammonium-N	930	23,450	10,000	---
Nitrate-N	1.4	8.7	---	62
Nitrite-N	<1.0	---	---	---
Silica (SiO_2)	4	128	17	16
Calcium	0	94	7.6	150
Magnesium	3.2	350	22	140
Sodium	45	1,600	320	3,700
Potassium	8	120	37	61
Organics				
5-day BOD	350	5,500	---	---
Organic C	2,200	19,000	4,700	986 (DOC)
Organic N	733	1,510	---	451

(continued)

TABLE 3-1 (continued)

Constituent	Concentration (mg/l)[a]			
	Minimum	Maximum	Median[b]	Retort no. 6[c]
Organics (continued)				
Oil and grease	3,800	3,800	---	30
Phenols	2.2	169	---	8.7
Volatile solids	2,070	119,300	---	---
Volatile acids	807	1,481	---	---
Trace elements				
Arsenic	0.46	10	1.8	0.07
Barium	0.002	0.47	0.07	0.8
Beryllium	<0.001	<0.001	---	---
Bromide	<0.001	1.94	0.082	---
Cadmium	<0.001	0.005	---	<0.2
Chromium	0.009	0.08	0.015	---
Cobalt	0.002	0.65	0.12	---
Copper	0.003	160	0.019	<0.2
Iron	0.091	77	7.6	2
Lead	0.002	0.83	---	---
Manganese	0.001	0.39	0.099	<0.2
Mercury	0.001	0.39	---	<0.2
Molybdenum	0.033	1.2	---	10
Nickel	0.014	2.6	---	0.1
Selenium	<0.001	1.7	---	<0.2
Silver	<0.001	0.23	---	---
Vanadium	0.004	>190	0.27	---
Zinc	0.020	15.1	0.28	0.1

[a] From Fox et al., 1978a.

[b] 50-percent probability of occurrence less than or equal to reported concentration; reported only when sample size was more than 15.

[c] Single sample, retort no. 6, Occidental Logan Wash (DA) Project, September 29, 1978. Presented here for rough comparison; does not necessarily represent expected values.

TABLE 3-2. CHARACTERIZATION OF RETORT WATER FROM (TRUE IN-SITU) RETORT NO. 9, ROCK SPRINGS, WYOMING, AND FROM MODIFIED IN-SITU RETORT

	Concentration (mg/l)	
Constituent	Rock Springs retort no. 9[a]	Logan Wash retort no. 6[b]
General water quality measures		
Total alkalinity ($CaCO_3$)	16,000 ± 500	540
Conductivity (μmhos/cm)	20,400 ± 3,840	---
Hardness ($CaCO_3$)[c]	110	---
pH (pH units)	8.65 ± 0.21	---
Solids, dissolved[d]	14,210 ± 223	13,000
Solids, total	14,210 ± 120	13,100
Major inorganics		
Bicarbonate[d]	15,940	659
Carbonate	500	<1
Sulfate	1,910 ± 130	4,000
Sulfide-S	0	---
Tetrathionate ($S_4O_6^=$)	280	---
Thiosulfate ($S_2O_3^=$)	2,740 ± 730	748
Thiocyanate (SCN^-)	136	---
Ammonia-N	3,830 ± 435	3.1
Ammonium-N	3,470 ± 830	---
Nitrate	0.17	62
Chloride	764 ± 92	240
Calcium	12 ± 4	150
Fluoride	62 ± 9	15
Magnesium	20 ± 6	140
Potassium	46 ± 10	61
Sodium	4,265 ± 272	3,700
Organics		
5-day BOD	740	---
Organic C	1,030 ± 105	986 (DOC)
Organic N	148 - 630	451
Oil and grease	580	30
Phenols	64 ± 34	8.7
Cyanide	0.42 - 0.90	---

(continued)

TABLE 3-2 (continued)

Constituent	Concentration (mg/l)	
	Rock Springs retort no. 9[a]	Logan Wash retort no. 6[b]
Trace elements		
Arsenic	1.0 ± 0.2	0.07
Barium	0.71 ± 0.33	0.8
Beryllium	<0.006	---
Boron	27 ± 7	<0.04
Bromide	2.3 ± 0.4	---
Cadmium	0.0016 ± 0.0008	<0.02
Chromium	0.02 ± 0.01	---
Cobalt	0.025 ± 0.016	---
Copper	0.09 ± 0.05	<0.02
Iron	1.2 ± 0.3	2
Manganese	0.09 ± 0.04	<0.02
Mercury	0.003 - 0.021	<0.02
Molybdenum	0.57 ± 0.16	10
Nickel	0.06 ± 0.02	0.1
Selenium	0.20 ± 0.12	<0.02
Silver	0.003 ± 0.001	---
Vanadium	0.12 ± 0.01	---

[a] Best value concentration determined as follows (from Fox et al., 1978a):

1. Smallest upper limit is reported unless that upper limit is for spark-source mass spectrometry analysis (SSMS); SSMS upper limit multiplied by three
2. Range is reported if coefficient of variation is greater than 100 percent
3. Single measurements shown as such and used as best value
4. Best values based on two or more measurements determined by Dixon's procedure after exclusion of values concluded to result from analytical error. Reported error is one standard deviation where more than one measurement made, otherwise estimated laboratory error reported.

[b] Single sample, retort no. 6, Occidental Logan Wash (DA) Project, September 29, 1978. Presented here for rough comparison; does not necessarily represent expected values.

[c] From Ca and Mg analysis.

[d] See Fox et al, 1978a for method of estimating carbonate species distribution.

However, these results show appreciable differences in ionic composition as the Logan Wash retort water showed considerably lower levels of alkalinity (and bicarbonate), thiosulfate, ammonia, chloride, fluoride, oil and grease, and phenols, with considerably higher levels of sulfate, nitrate, calcium, and magnesium. Differences in oil shale retorted, retorting conditions, and perhaps analytical procedure contributed to these differences.

Fox et al. (1978a) discuss analytical problems associated with the characterization of retort waters. They conclude that:

- Significant problems exist with use of standard analytical techniques for complex waters such as retort waters
- Instrumental methods are generally more accurate than chemical methods
- Sample handling can appreciably affect results
- Existing methods may be adequate for the measurement of sulfate, inorganic carbon and ammonia
- Methods development is needed for routine measurement of cyanide, COD, phenols, orthophosphate, solids, and sulfide.

For the alternative analytical methods evaluated, the following was concluded:

- Spark source mass spectrometry produced lowest detection limits but poorest precision
- X-ray fluorescence and neutron activation analysis produced precise and accurate results
- Atomic absorption is acceptable for measurement of Ca, Mg, Fe, Na, Si, As, K, Se, and Zn.

Some of the other available data on the chemical characteristics of in-situ retort water are listed in Table 3-3. Of particular note here is the wide differences between simulated in-situ retort water and that collected at Rock Springs from true in-situ retorts. This is particularly true for conductivity, sodium, bicarbonate, carbonate, fluoride, organic carbon (DOC), and organic nitrogen (Kjeldahl nitrogen).

IN-SITU SPENT SHALE

In addition to retort water, a significant source of groundwater impact is the materials which may be leached from abandoned in-situ retorts into adjacent aquifers. A summary of the characteristics of these potential contaminants is presented in the following paragraphs.

Amy, Thomas, and Hines (undated) evaluated the leaching of organics from shale retorted in a simulated in-situ retort. Both inert (N_2) atmosphere and combustion retorting conditions were considered. Only the combustion

TABLE 3-3. CHARACTERISTICS OF IN-SITU RETORT WATER REPORTED IN AVAILABLE LITERATURE

Constituent	Concentration (mg/l)	Reference[a]
Total dissolved solids	3,000	b
Conductivity (µmhos/cm)	25,000	c-1
	48,000	c-2
pH (pH units)	8.5 - 9.5	b
	8.5	c-1
	8.6	c-2
Calcium	8	c-1
	4	c-2
Magnesium	12	c-1
	16	c-2
Potassium	43	c-1
	24	c-2
Sodium	3,100	a
	4,100	c-1
	188	c-2
Bicarbonate (HCO_3)	15,000	c-1
	33,400	c-2
Carbonate (CO_3)	19,200	a
	2,100	c-1
	14,900	c-2

(continued)

TABLE 3-3 (continued)

Constituent	Concentration (mg/l)	Reference[a]
Chloride	13,410	a
	3,900	c-1
	2,800	c-2
Sulfate (SO_4)	4,450	a
	1,400	c-1
	1,340	c-2
Fluoride	56	c-1
	12	c-2
Thiosulfate ($S_2O_3^=$)	3,000	c-1
	2,050	c-2
Ammonia -- NH_4^+	4,800	a
NH_3	2,500	b
NH_4^+-N	3,800	c
TOC	2,150	b
DOC	1,000	c-1
	5,000	c-2
COD	6,700	b
Total Kjeldahl nitrogen	4,000	c-1
	18,000	c-2

[a] References:

a - Hubbard (undated), water from Rock Springs tests

b - Pfeffer (1974), simulated in-situ data

c - Stuber and Leenheer (1978): data from Rock Springs No. 9 test (c-1), and simulated in-situ (LERC 150-ton) retort (c-2) retorted shale experiments will be considered here, as these most closely correspond to proposed MIS operations on Tracts C-a and C-b. Experimental characteristics are as follows:

Experiment no.	Retort 1	Retort 3
Input gas	Air + N_2 (7.6% O_2)	Air + recycle gas (10.5% O_2)
Maximum retort temperature (°C)	750	935
Retorting rate (meters per day)	0.69	1.34
Spent shale organic content (percent by weight)	0.2	2.1

The relatively low organic levels in spent shale 1 result from combustion of residual organics during retorting. The elevated levels in spent shale 3 are due to adsorption or condensation of organics from the recycle gas behind the flame front in the retort.

Thirty-day batch leaching experiments using varying water temperatures (approximately room temperature and 80°C to simulate water entering an uncooled retort) and varying water quality (distilled water and simulated groundwater, intended to approximate Lower Aquifer water from the Piceance Basin), were conducted:

		TOC (milligrams per 100 grams spent shale)	
Leaching water	Temperature (°C)	Shale 1	Shale 3
Distilled	20	1.1	3.5
Distilled	80	1.3	2.9
Synthetic groundwater	20	1.0	3.8
Synthetic groundwater	80	1.0	3.4

No great differences can be seen in leachate quality due to changes in either water temperature or initial water quality.

Equilibrium batch experiments, wherein varying amounts of leachate water were added to processed shale and allowed to equilibrate, were also conducted with the following results from spent shale 1:

Mass spent shale (grams)	50	50	50	50
Volume water added (milliliters)	30	50	100	200

Leaching water	Temperature (°C)	TOC (milligrams per 100 grams spent shale)			
Distilled	20	1.1	1.1	1.0	1.6
Distilled	80	1.0	1.3	1.4	2.0
Synthetic groundwater	20	1.1	1.0	1.4	1.4
Synthetic groundwater	80	1.0	1.0	1.5	1.8

Using estimates provided earlier of the amounts of spent shale to be left in place on Tracts C-a and C-b, the following amounts of potentially leachable carbon are estimated:

Tract	Amount in-situ spent shale (tons)	Assumed leachable amount (mg/100 g)	Leachable amount (tons)
C-a	$9.8 - 14.4 \times 10^8$	2.0	$2.0 - 2.9 \times 10^4$
C-b	$1.5 - 2.2 \times 10^9$	2.0	$3.0 - 14.4 \times 10^4$

Other observations reported by Amy and Thomas (undated) on the above and a series of continuous flow experiments indicated that the leaching of organics was also influenced by particle size. Because a greater surface area is available for leaching, smaller particle sizes yield more leached materials. Also, the amount of organic matter leached (i.e., TOC concentration) generally increased with time as did inorganics (as indicated by increasing specific conductance), although minor decreases were also noted occasionally. In general, during the continuous flow experiments, the rate of leaching was greatest during the first day with approximate equilibrium being reached by the tenth day.

At the tenth day of batch experiment exposure, analysis of leachate waters for spent shale 1 indicated about 10 mg/l TOC and 8000 µmhos per centimeter specific conductance. Continuous flow experiments yielded leachate of 20 to 25 mg/l TOC and 6000 µmhos per centimeter specific conductance after 10 days (Amy and Thomas, undated). It should be noted that these experiments were conducted using distilled water. Groundwaters of varying quality may produce different results.

The observed distribution of major organic fractions from batch leaching experiments using simulated in-situ, combustion retorted spent shale is as follows (LBL, 1978):

		Leached amount (milligrams per 100 grams)			
Leaching water	Temperature (°C)	Total	Acid	Base	Neutral
Distilled	20	850-2,000	290-680	360-460	200-860
Distilled	80	640-1,290	110-500	240-610	180-290

(continued)

Leaching water	Temperature (°C)	Leached amount (milligrams per 100 grams) Total	Acid	Base	Neutral
Synthetic groundwater	20	1,450	420	370	660
Synthetic groundwater	80	1,190	500	330	360

The amounts of each fraction leached using the synthetic groundwater was within the range of observations using distilled water.

An assessment of in-situ leaching processes by Lawrence Berkeley Labs (LBL, 1978) notes the difficulties of evaluating inorganic leachate quality due to the great spatial variability in inorganic character of oil shale. Also, variation in the quality of groundwater can be expected to appreciably affect the leaching process. Among the water quality constituents important in this manner are alkalinity (which is related to the potential for carbonate precipitation) and TDS (which may affect ion exchange processes or produce common ion effects which influence solution processes and equilibria). Discussion of these phenomena is presented in Section 7, Potential Pollutant Mobility.

Summaries of experimental data on the concentration of various constituents in leachate from surface and in-situ retorted shale are shown in Table 3-4. These data show that leachate from in-situ spent shale may be (1) lower than leachate from surface retorted shale with regard to the concentration of TDS, fluoride, sulfate, nitrate, magnesium, sodium, potassium, boron, and molybdenum, and (2) higher than surface retorted shale with regard to the concentration of carbonate.

These data (Table 3-4) were used by LBL (1978) to group constituents according to the amount of material potentially leached from in-situ processed shale:

1. Less than 10 mg per 100 g: NO_3, Cl, F, Mg, Al, B, Cr, Fe, Li, Mo, Pb, Sr, Zn
2. Between 10 and 100 mg per 100 g: HCO_3, OH, K, Si
3. Greater than 100 mg per 100 g: CO_3, SO_4, Ca, Na.

Assuming the adequacy of these estimates, the potential amount leached from abandoned in-situ retorts can be estimated as follows:

Tract	Amount in-situ spent shale (tons)	Category:	Leachable amount (10^5 tons) 1	2	3
C-a	$9.8 - 14.4 \times 10^8$		<1.4	0.98 - 14.4	> 9.8
C-b	$1.5 \times 2.2 \times 10^9$		<2.2	1.5 - 22	>15

TABLE 3-4. SUMMARY OF LITERATURE ON LEACHATE (USING DISTILLED WATER) FROM SIMULATED IN-SITU RETORTED SHALE AND FROM SURFACE RETORTED SHALE (LBL, 1978)

Constituent	Simulated in-situ retorts	Surface retorts[a]
General water quality measures		
pH	7.8 - 12.7	7.8 - 11.2
Total dissolved solids	80 - >2,100	970 - 10,011
Major inorganics		
Bicarbonate	22 - 40	20 - 38
Carbonate	30 - 215	21
Hydroxide	22 - 40	---
Chloride	5.5	5 - 33
Fluoride	1.2 - 4.2	3.4 - 60
Sulfate	50 - 130	600 - 6,230
Nitrate (NO_3)	0.2 - 2.6	5.1 - 5.6
Calcium	3.6 - 210	42 - 114
Magnesium	0.002 - 8.0	3.5 - 91
Sodium	8.8 - 235	165 - 2,100
Potassium	0.76 - 18	10 - 625
Organics		
Total organic carbon	0.9 - 38	---
Trace elements		
Aluminum	0.095 - 2.8	---
Arsenic	---	0.10
Boron	0.075 - 0.14	2 - 12
Barium	---	4.0
Chromium	0.002 - 1.8	---
Iron	0.0004 - 0.042	---
Lead	0.014 - 0.017	---
Lithium	0.020 - 0.42	---
Molybdenum	trace	2 - 8
Selenium	---	0.05
Silica	25 - 88	---
Strontium	0.004 - 8.7	---
Zinc	0.001 - 0.025	---

[a] TOSCO, U.S. Bureau of Mines, and Union Oil Company processes.

Thus, modified in-situ developments, such as proposed on Tracts C-a and C-b, result in a large potentially leachable mass.

Estimates of the potentially leachable quantities of trace inorganics are listed in Table 3-5. Elements for which estimates of leachable quantity are greater than 1 milligram per 100 grams (or 10^{-5} tons per ton spent shale) are boron, cerium, chloride, manganese, rubidium, nickel, vanadium, barium, and phosphorus.

The data presented above are largely for laboratory and simulated in-situ experiments. As previously noted, actual leaching processes can be expected to vary with geographic location, characteristics of retort operation, and quality of groundwater moving through the retort zone. As one example of data from a field-scale experiment, data listed in Table 3-6 show the observed influence of spent in-situ oil shale on groundwater quality. These data, taken from a Wyoming test site, show very large increases in concentration, particularly sodium sulfates and bicarbonates. Note that these constituents are also listed above as having a large potential for leaching from in-situ spent oil shale.

TABLE 3-5. ESTIMATED QUANTITIES OF MATERIAL LEACHED FROM SPENT SHALE (LBL, 1978)

Element	Quantity leached[a] (mg/100 g)	Element	Quantity leached[a] (mg/100 g)
Ag	<0.00002-0.026	Mo	<0.009-1.3
As	<0.003-1.3	Nb	<0.001-0.30
B	<0.012-3.5	Nd	<0.024-1.2
Ba	<0.061-11	Ni	<0.028-11
Be	<0.00018-0.084	P	<0.5->75
Bi	<0.0001-0.092	Pb	<0.001-1.1
Br	<0.0003-0.90	Pr	<0.0006-0.28
Cd	<0.00002-0.021	Rb	<0.011-6.8
Ce	<0.04-3.2	Sb	<0.0002-0.17
Cl	<0.028->150	Sc	<0.00012-1.0
Co	<0.00078-0.32	Se	<0.0008-0.078
Cs	<0.00006-0.16	Sm	<0.0005-0.14
Cu	<0.017-1.8	Sn	<0.0004-0.069
Dy	<0.00027-0.059	Ta	<0.0004-0.072
Er	<0.00001-0.021	Tb	<0.00013-0.017
Eu	<0.00018-0.030	Te	<0.0003-0.005
Ga	<0.001-0.27	Th	<0.001-0.18
Gd	<0.00006-0.27	Ti	<0.15-47
Ge	<0.00037-0.044	Tl	<0.0003-0.021
Hf	<0.0006-0.060	Tm	<0.00003-0.003
Hg	<0.0001-0.032	U	<0.0003-0.12
Ho	<0.00005-0.007	V	<0.010-4.2
I	<0.0001-0.44	W	<0.00003-0.044
La	<0.0011-0.75	Y	<0.0018-0.75
Lu	<0.00006-0.0077	Yb	<0.00024-0.038
Mn	<0.009-5.7	Zr	<0.003-0.90

[a] Range corresponds to 1 to 15 percent of content in raw oil shale as reported in LBL, 1978 (Poulson et al., 1977).

TABLE 3-6. WATER QUALITY ANALYSIS OF GROUNDWATER NEAR TRUE IN-SITU OIL SHALE EXPERIMENT (DATA FROM JACKSON et al., 1975)

Constituent	Concentration (mg/l)[a]			Change from before burn[b]	
	Before burn	Initial leaching period	4 years after burn	Observed change from initial leaching	Observed change over longer term
pH	9.7	8.6	9.3	0.89	0.96
TDS	5,029	30,030	10,721	5.97	2.13
Bicarbonate (HCO_3)	1,300	9,750	3,046	7.50	2.34
Carbonate (CO_3)	671	1,940	1,032	2.89	1.54
Sulfate (SO_4)	254	4,810	2,400	18.94	9.45
Nitrate (NO_3)	1.2	4.5	-	5.40	-
Chloride (Cl)	931	4,250	592	4.56	0.64
Fluoride (F)	9.1	53	25	5.82	2.75
Calcium (Ca)	11	58	2.7	2.54	0.25
Magnesium (Mg)	4.7	230	6.1	48.94	1.30
Sodium (Na)	1,830	8,900	3,460	4.86	1.89
Potassium (K)	6.9	34	101	4.93	14.64
Boron (B)	11	-	40	-	3.64

[a] Data are averages for a set of well water samples.

[b] Ratio of observed concentration (or pH level) at indicated time to before-burn concentration.

SECTION 4

GROUNDWATER USE

Beyond use by oil shale developers, there is no extensive use of groundwater from aquifers beneath Tracts C-a and C-b. This is likely due to groundwater quality and depth considerations, availability of surface water sources, and the general limited agricultural, livestock, industrial, and municipal development in the region.

Approximately 5100 acres of land in the Piceance Creek watershed are irrigated for hay and pastureland. Substantial withdrawals are made in the months of April and May. Approximately 200 acres in the Yellow Creek watershed are irrigated using Yellow Creek water.

As will be noted in Sections 5 and 6, the aquifers beneath Tracts C-a and C-b are believed to discharge near the basin center into the surface drainages of Piceance and Yellow Creeks. These creeks, in turn, discharge to the White River and subsequently into the Green and Colorado River systems. Hence, although direct use of groundwaters is limited, groundwater quality perturbations may influence a variety of municipal and agricultural water uses downstream in the Colorado River Basin.

SECTION 5

HYDROGEOLOGIC FRAMEWORK

In this section, the general climate, physiography, geology, and hydrology of the study area are presented, along with site-specific data on Tracts C-a and C-b.

CLIMATE

The Piceance Basin is characterized by semiarid montane climate. There is considerable variation between the center of the basin and its high rim. Summer temperatures in the lower northern areas average near 75°F, while the western and northern highlands may be 15 degrees cooler. The temperature differential between the basin highlands and the center in the winter is less, but even near the White River temperatures can average below freezing.

The majority of the precipitation occurs as winter snowfall. Most of this snow falls on the highlands. Winter precipitation there can reach 16 inches, but at low elevations may only be 6 inches. Summer rainfall follows the same pattern, with only 6 inches at low elevation and up to 10 inches along the rim.

The high summer temperatures coupled with low humidity create a high evapotranspiration rate. In the low areas, it far exceeds available precipitation. The longer cool season and large amount of winter snow at high elevations raise the precipitation:evapotranspiration ratio.

PHYSIOGRAPHY

Topography and Setting

The Piceance Basin is set in a wide plateau area between the Colorado Rockies and the Wasatch Range (Figure 5-1). The entire drainage of this area is tributary to the Colorado River. The Piceance Basin itself is roughly circular in shape. It is bounded on the west by the Cathedral Bluffs, to the top of which the basin slopes gently up from its center. On the south, this slope flattens into the Roan Plateau, which drops off suddenly at the Roan Cliffs into Parachute Creek and Roan Creek Valleys. On the east, the Grand Hogback provides a less dramatic boundary. The White River, into which the basin drains, is the northern boundary.

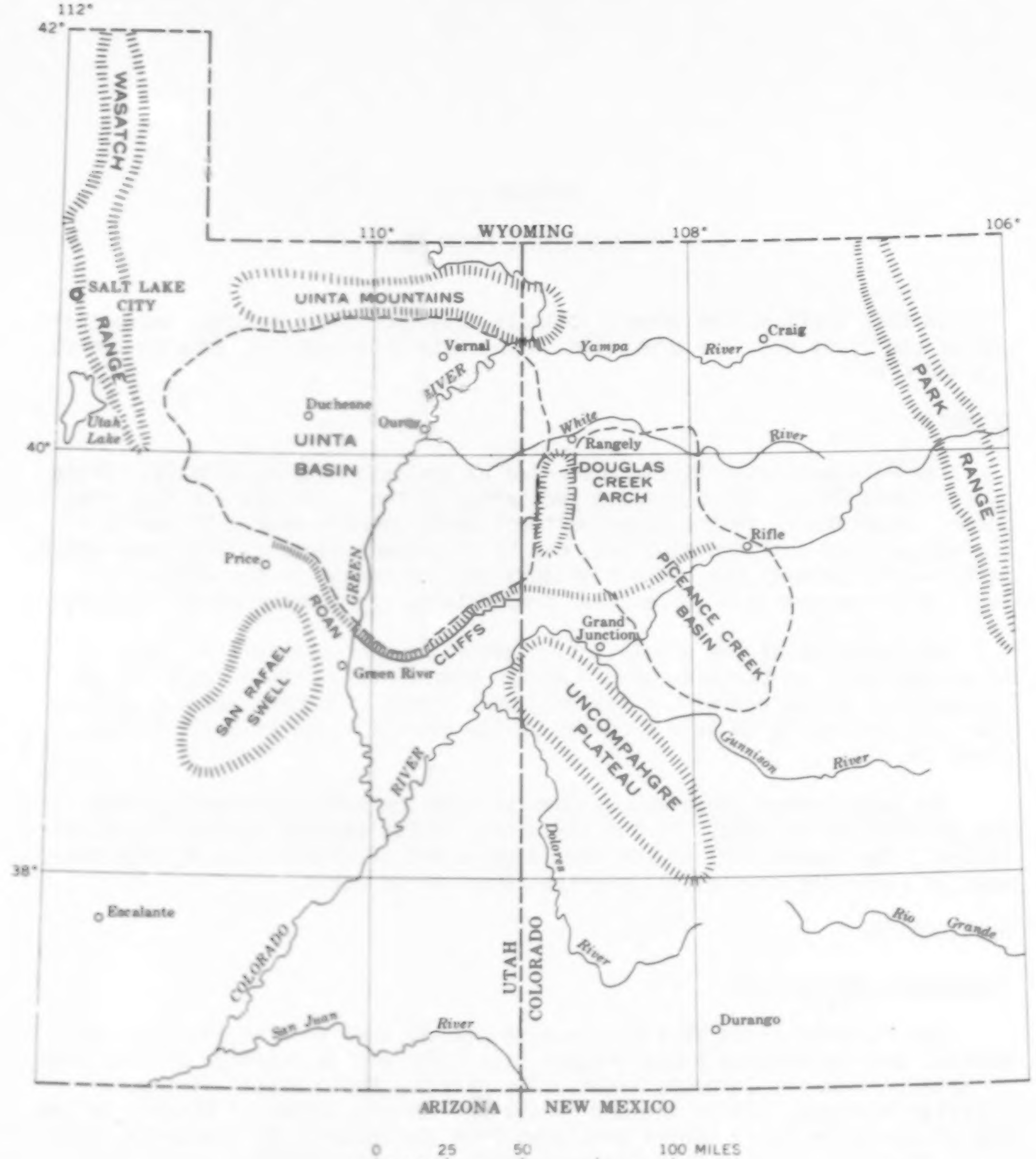

112°
42°
WASATCH
SALT LAKE CITY
RANGE
Utah Lake
110°
WYOMING
108°
106°
UINTA MOUNTAINS
Vernal
Yampa
River
Craig
PARK
RANGE
Duchesne
Ouray
RIVER
UINTA
BASIN
White
Rangely
River
40°
DOUGLAS
CREEK
ARCH
Rifle
PICEANCE CREEK
BASIN
Price
GREEN
ROAN
CLIFFS
Grand Junction
SAN RAFAEL
SWELL
Green River
UNCOMPAHGRE
PLATEAU
Gunnison
River
RIVER
Dolores
38°
Escalante
COLORADO
Rio
Grande
River
UTAH
COLORADO
San Juan
River
Durango
ARIZONA
NEW MEXICO
0
25
50
100 MILES

Figure 5-1. Major structural features in study area (modified from Cashion, 1967). Locations of Tracts C-a and C-b within Piceance Basin are shown in Figure 5-3.

Landforms

The basin has the rough configuration of a shallow bowl. There are few topographic irregularities or distinctive features. This sloping bowl shape has been dissected at regular intervals by streams draining from the high edges of the basin. Thus, most of the relief is provided by stream erosion. In the eastern center of the basin, the Dry Fork of Piceance Creek and the main fork have cut headward toward each other, leaving an isolated highland between them. The elevation of the basin ranges from nearly 9000 feet around the western and southern margin to below 6000 feet at the White River.

Drainage Patterns

The Piceance Basin is drained by two streams, Yellow Creek and Piceance Creek. These both empty into the White River, which flows into the Green River, a tributary to the Colorado. Both Yellow and Piceance Creeks extend to a position near the center of the basin before they receive significant inflow. From this point they are joined at regular intervals by radial, bifurcated tributaries. The tributaries flow in nearly straight paths from the rim of the basin to the main drainage. The tributaries flow in moderately to deeply incised valleys. This unusually lineal drainage pattern may be attributed to the incision of initially high-gradient streams on a smooth upland into very homogeneous sediments. In a few places the stream pattern may be observed to follow the predominant northwest-northeast joint set.

REGIONAL STRATIGRAPHY

A generalized geologic section of the Piceance Basin is shown in Figure 5-2.

Wasatch Formation

The Early Eocene Wasatch Formation is composed of fluvial red and gray shale and siltstone interbedded with massive gray to brown sandstone. The bedding is generally irregular and discontinuous. The formation is exposed continuously around the margin of the Piceance Basin. It is thickest on the eastern side of the basin, over 5500 feet in places, but thins to only a few hundred feet in some locations on the western side.

Green River Formation

The Green River Formation was deposited on the fluvial sandstones of the Wasatch Formation. The identifying characteristic of the Green River Formation is its lacustrine nature. The chemically reduced environment of the ancient lake bed created drab white and gray sediments which contrast strongly with the red and brown tones of the Wasatch Formation. The Green River Formation is divided into four lithologic units: the Douglas Creek, Garden Gulch, Anvil Points, and Parachute Creek Members.

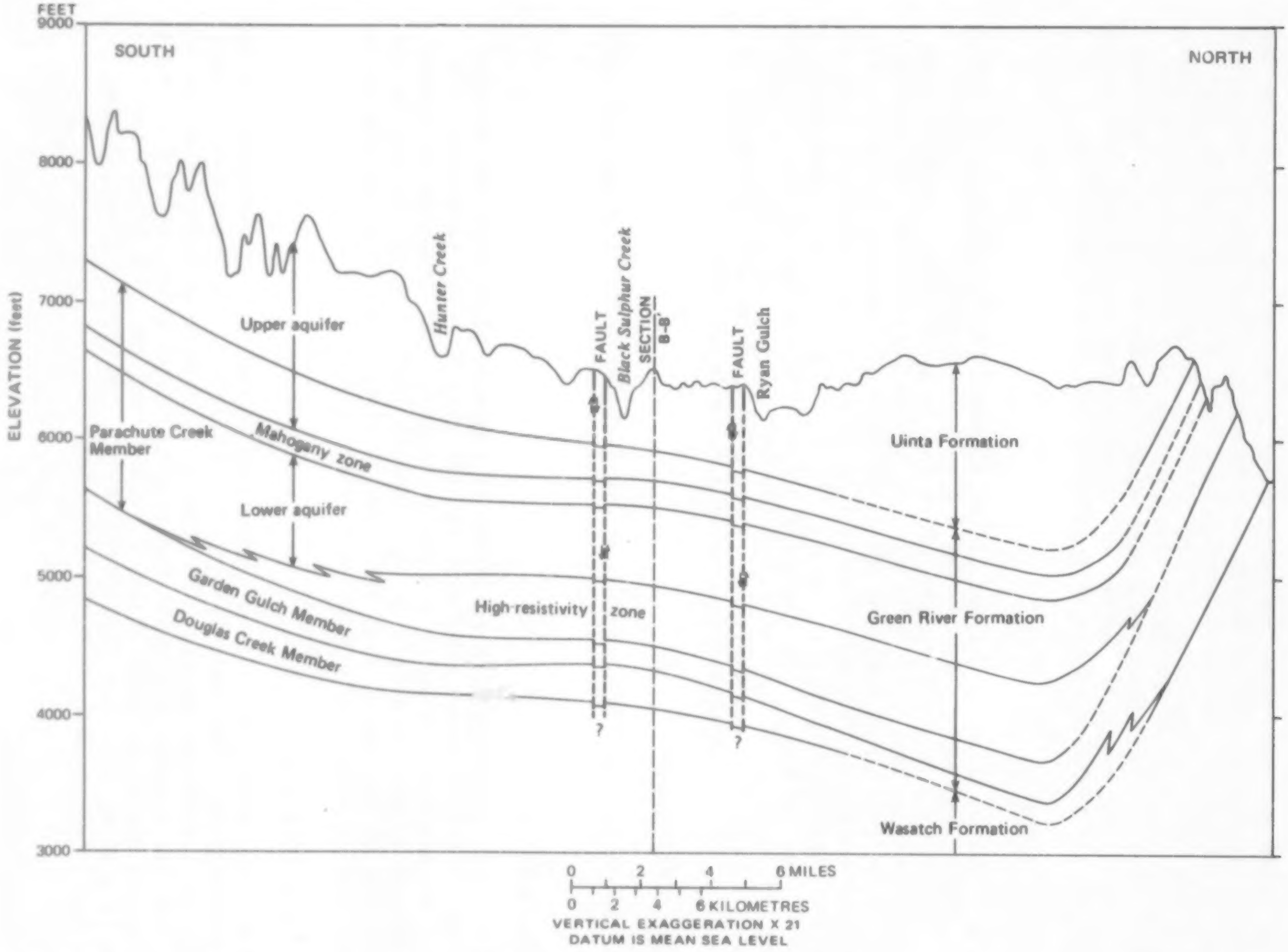

FEET
9000
8000
7000
6000
5000
4000
3000
ELEVATION (feet)
SOUTH
NORTH
Hunter Creek
FAULT
Black Sulphur Creek
SECTION B-B'
FAULT
Ryan Gulch
Upper aquifer
Parachute Creek Member
Mahogany zone
Lower aquifer
Garden Gulch Member
Douglas Creek Member
High-resistivity zone
?
?
Uinta Formation
Green River Formation
Wasatch Formation
0 2 4 6 MILES
0 2 4 6 KILOMETRES
VERTICAL EXAGGERATION X 21
DATUM IS MEAN SEA LEVEL

Figure 5-2. Geologic section through the Piceance Basin along north-south line between Tracts C-a and C-b (Weeks et al., 1974).

Douglas Creek Member--

The Douglas Creek Member dates from the Early to Middle Eocene. This member is characterized by fine- to medium-grained quartz sandstone, interbedded with shale, siltstone, and limestone. Most of the limestone is oolitic or algal, and some is ostracodal, occurring in thin to massive beds. The member contains little oil shale. Bedding is even, and laterally continuous.

The Douglas Creek Member intertongues extensively with the underlying Wasatch Formation. The fluvial Wasatch tongues are commonly difficult to distinguish from the lacustrine Douglas Creek Member due to the close relationship of the environments of deposition.

The Douglas Creek Member crops out on the western side of the basin, where it exceeds 800 feet in thickness. The thickness decreases toward the east and beneath the center of the basin. The Douglas Creek Member grades laterally into the sandy facies of the Anvil Points Member.

Garden Gulch Member--

The Garden Gulch Member represents an early playa-lake center environment. This member is composed of fine-grained sediments, mostly thin or papery shale, with some marlstone and a few thin sandstone and limestone beds. The member differs from the overlying Parachute Creek Member primarily in the smaller amount of oil shale it contains. Near the basin center, the Garden Gulch Member ranges from 1000 feet near the depositional center to about 90 feet near the western basin margin.

Anvil Points Member--

The Anvil Points Member is the shore facies on the eastern side of the basin. Very heterogeneous in composition, it contains a slight preponderance of gray shale, with a large amount of sandstone (which occurs both thinly interbedded with the shale and in massive strata), some marlstone, siltstone, and algal and oolitic limestone. The member conformably overlies the Wasatch Formation and conformably underlies the Parachute Creek Member of the Green River Formation, intertongueing with both of these units. The maximum thickness of the member is 1800 feet. This thickness decreases to zero a short distance from the eastern margin of the basin by gradation into stratigraphically equivalent units.

Parachute Creek Member--

The Parachute Creek Member sediments were deposited in the center of a very large saline playa. The sediments around the center of the basin are largely marlstone, with some oil shale. The basal deposits in the center of the depositional basin are mainly evaporites, nahcolite ($NaHCO_3$), and dawsonite [$NaAl(OH)_2CO_3$], and halite ($NaCl$). Some oil shale is interbedded with these evaporites, which attain a maximum thickness of over 1000 feet in the center of the basin. Above the saline zone is a section of very rich oil shale known as the Mahogany Zone. This zone is present over the entire area of the basin and is also present in the Uinta Basin of Utah. Above the

Mahogany Zone, which ranges from less than 3 to about 100 feet in thickness, the formation consists of interbedded marlstone and oil shale. The thickness of the entire member varies from 1800 feet to less than 600 feet.

Uinta Formation

The beds of the Uinta Formation record a return to fluvial conditions. The Uinta Formation is composed of sandstone, marlstone, siltstone, and shale. The proportion of sandstone increases toward the top of the formation. The formation is generally conformable with the underlying Parachute Creek Member, but is locally unconformable. In places, the contact has been distorted by plastic flow of the fine-grained Green River sediments beneath the load of the denser Uinta sandstones.

STRUCTURE

The Piceance Basin is asymmetric in shape, steepest on the north and east sides, and gently sloping on the south and west. The dip at the northern end of the basin ranges between 15 and 30 degrees, while on the south it is less than 1 degree in places. The Douglas Creek Arch separates the Piceance Basin from the Uinta Basin to the west. The Uncompahgre Uplift bounds the basin to the south and the Grand Hogback to the east. The basin terminates on the north in the complex system of major anticlines (including the Rangely and Blue Mountain Anticlines) tributary to the Uinta Mountain uplift. The gross structure of the basin has experienced only minor distortion from local deformation. Northeast-southwest stresses have created a series of northwest trending anticlines. These features are gentle (Figure 5-2) and in harmony with the general trend of the basin.

Several small faults have been mapped in the center of the basin, between Federal Prototype Lease Tracts C-a and C-b. These faults trend northwest and southeast, and generally show less than 50 feet of displacement. Several of them are double faults with a small graben between.

GENERAL BASIN HYDROGEOLOGY

The area contains three important aquifer systems: the Lower Aquifer, the Upper Aquifer, and the alluvial aquifers. The Lower Aquifer occurs in the Parachute Creek Member below the Mahogany Zone and the Upper Aquifer is above the Mahogany Zone. The alluvial aquifer system occurs in the stream valley bottoms.

Lower Aquifer

The Lower Aquifer is bounded generally on the top by the Mahogany Zone and on the bottom by the shales of the Garden Gulch Member. Porosity is mostly secondary, resulting from fracturing and jointing of the marlstone and oil shale of the lower Parachute Creek Member. Porosity also results from the solution of the evaporite minerals in the saline section at the base of the Parachute Creek Member. Removal of these soluble minerals by groundwater has created a zone of high permeability at the top of the saline section known as the leached zone. The saline section below the leached zone still contains its original salts. Because of the high electrical resistivity of the salts which characterizes this zone on geophysical logs, it is called the "high resistivity" or "HR" zone. Inasmuch as both the high kerogen content oil shales and the saline minerals of the high resistivity zone are rather ductile, the HR zone has experienced little fracturing and has a low permeability. Because of these characteristics, in the center of the basin the high resistivity zone forms the lower confining stratum.

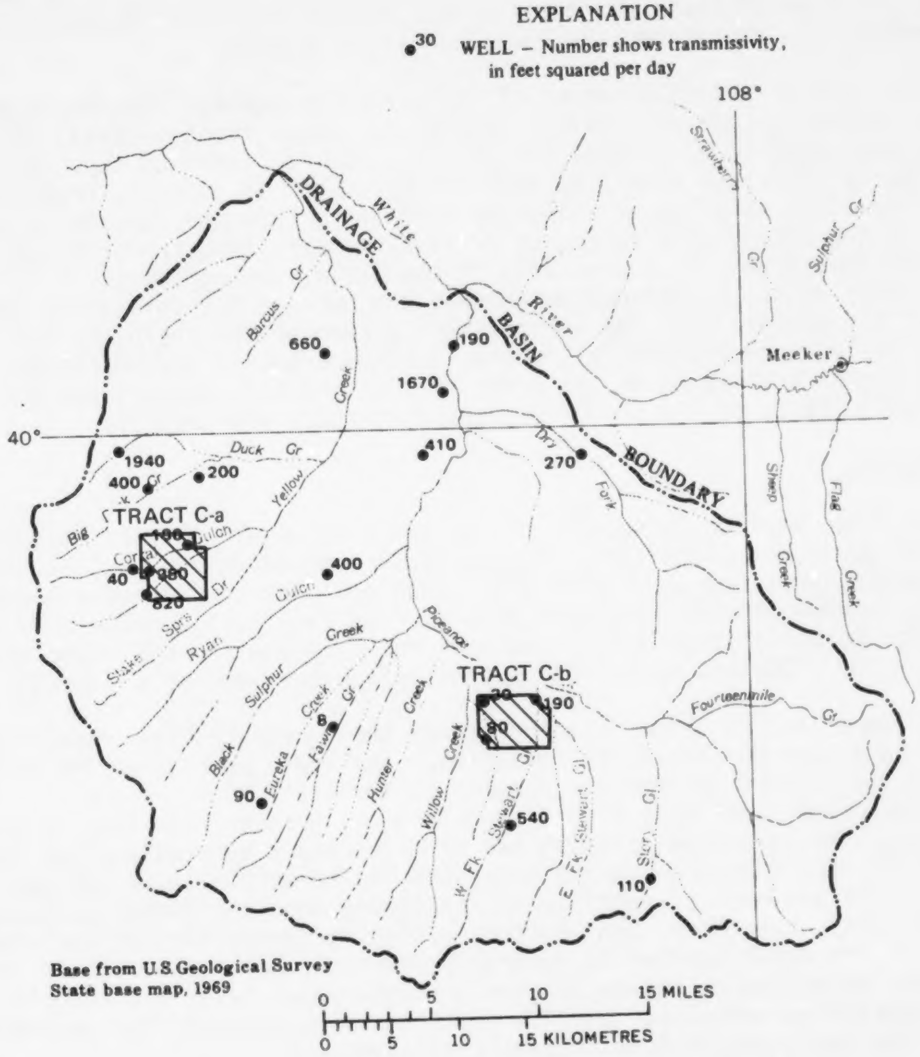
The fracture-solution nature of this confined aquifer results in heterogeneous hydraulic characteristics. Figure 5-3 shows transmissivity (T) values computed by Weeks et al. (1974) for specific aquifer tests on the Lower Aquifer. The values range from 8 to 1940 ft^2 per day. In general, transmissivity increases with the soluble mineral content from the margins to the center of the basin. The degree of fracturing, resulting from deformation, increases toward the structural axis of the basin, and northwest along the axis. Weeks et al. (1974) estimated that the average transmissivity varies from 130 ft^2 per day near the southeastern corner of the basin, to 670 ft^2 per day in the area between Yellow and Piceance Creeks. They estimated the storage coefficient to be on the order of 10^{-4} and the specific yield to be 10^{-1}. Well yields of 200 to 400 gallons per minute are typical.

Upper Aquifer

The Upper Aquifer is separated from the Lower Aquifer by the Mahogany Zone. Although no interaquifer response was observed during vertical permeability tests, Weeks et al. (1974) have concluded that considerable movement of water between the aquifers does occur. They base this conclusion on the fact that the water level in the two aquifers rarely differs by more than 100 feet over the 1200-foot head drop of the two aquifers across the basin.

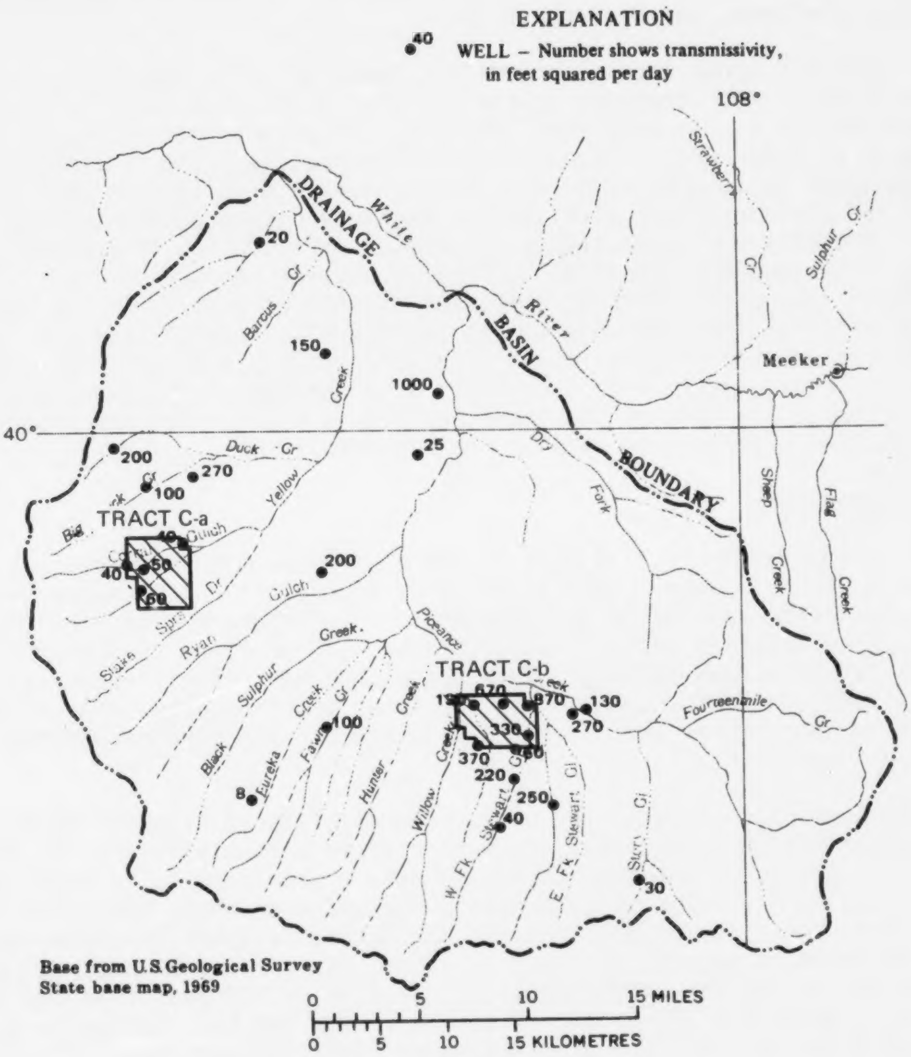
The Upper Aquifer zone is comprised of the Parachute Creek Member above the Mahogany Zone and the Uinta Formation. The lower portion of the Uinta Formation is divided by numerous tongues of the Green River Formation. Although the primary porosity of the sandstones is greater than that of the marlstones, the sandstone porosity has been decreased by precipitates from groundwater, while fracturing has increased the permeability of the marlstones, which are more susceptible to fracturing than the Uinta sandstones. The sandstones, therefore, tend to form confining layers for the marlstone aquifers. The Upper Aquifer is generally confined, but is unconfined in many locations, depending on the relationship of the water level and the lithology. Strata containing nahcolite solution cavities which occur in the southern part of the basin should form transmissive layers.

The transmissivity varies with saturated thickness, degree of fracturing, degree of solution, and location of wells with regard to fractures. Calculated T values shown in Figure 5-4 range from 8 to 1000 ft^2 per day. As both the saturated thickness and the degree of solution increase toward the basin center, the transmissivity does also. Weeks et al. (1974) considered representative values to be 70 ft^2 per day around the rim, 130 ft^2 per day in the area around the center, and 270 ft^2 per day in the center.


EXPLANATION
30
WELL – Number shows transmissivity, in feet squared per day
108°
40°
DRAINAGE
BASIN
BOUNDARY
White
River
Strawberry
Cr
Sulphur
Cr
Meeker
Barcus
Cr
Creek
660
190
1670
410
270
Dry
Fork
Duck
Cr
1940
400
200
Yellow
TRACT C-a
Big
Gulch
Corral
100
280
40
820
Dr
400
Gulch
Stake
Sprs
Ryan
Greek
Piceance
Sheep
Greek
Flag
Greek
TRACT C-b
20
190
80
Fourteenmile
Cr
Black
Sulphur
Creek
Fawn
Cr
8
Eureka
90
Hunter
Creek
Willow
Creek
W. Fk.
Stewart
Gl
E. Fk.
Stewart
Gl
540
Story
Gl
110
0
5
10
15 MILES
0
5
10
15 KILOMETRES

Base from U.S. Geological Survey State base map, 1969

Figure 5-3. Distribution of transmissivity in the Lower Aquifer, Piceance Basin (Weeks et al., 1974).


EXPLANATION
40 WELL – Number shows transmissivity, in feet squared per day
108°
40°
DRAINAGE
BASIN
BOUNDARY
White
River
Strawberry
Sulphur Cr
Meeker
Barcus Cr
Creek
Duck Cr
Yellow
Dry
Fork
Sheep Creek
Flag Creek
TRACT C-a
Big
Gulch
Spring
Dr
Gulch
Stake
Ryan
Creek
Piceance
Sulphur
Black
Eureka
Creek
Fawn Cr
Hunter
Creek
Willow
Creek
TRACT C-b
Creek
Fourteenmile Gr
W. Fk. Stewart Gl
E. Fk. Stewart Gl
Stewart Gl
Gl
20
150
1000
25
200
100
270
40
50
40
60
200
100
8
190
670
870
130
270
330
370
560
220
250
40
30
0
5
10
15 MILES
0
5
10
15 KILOMETRES

Base from U.S. Geological Survey State base map, 1969

Figure 5-4. Distribution of transmissivity in the Upper Aquifer, Piceance Basin (Weeks et al., 1974).

Porosity ranges from 10 percent to 1 percent. It is highest in the center, where solution cavities are present, and least around the edges. The calculated storage coefficient is on the order of 10^{-3}, indicating at those locations confined conditions with nearby unconfined conditions. The total storage is probably somewhat less than that in the Lower Aquifer due to less saturated thickness and less porosity.

Figure 5-5 shows the potentiometric level of wells open to both the Upper and Lower Aquifers. Inasmuch as the difference in water level between the two aquifers is rarely more than 100 feet, the potentiometric map of either the Upper or Lower Aquifer should not differ greatly. The potentiometric reconfiguration is determined by the transmissivity distribution and the recharge and discharge characteristics. Recharge occurs around the rim of the basin. Probably the major source is gradual infiltration of snowmelt in the spring. The downward potential difference between the two aquifers around the rim of the basin indicates that most of the recharge is to the Upper Aquifer and that the Lower Aquifer is recharged by leakage from the Upper Aquifer through the Mahogany Zone. The water migrates toward the center of the basin, where, in certain locations, it discharges to Piceance and Yellow Creeks. Here, the head of the Lower Aquifer is higher than the Upper, and Lower Aquifer discharge is through the Upper Aquifer.

Alluvial Aquifers

Alluvial sediments line most of the major stream valleys and are usually saturated at their base. This alluvium is thickest along Piceance and Yellow Creeks; near the confluence with the White River there may be over 100 feet of saturated alluvium below Piceance Creek. All of these aquifers follow the shape of their stream valleys. They are recharged in their upper reaches from streams and from snowmelt. In the lower sections, they are recharged from the deep aquifers and, in turn, discharge to the streams, maintaining the base flow.

The hydraulic conductivity of such unconsolidated alluvial deposits is high and this high conductivity is reflected in transmissivities of 2700 to 20,000 ft^2 per day. The unconsolidated nature also results in high specific yields, on the order of 20 percent. In spite of these favorable aquifer parameters, the alluvial aquifers are not desirable areas for large-scale water development because of the small total storage and boundary effects created by the aquifer morphology. In addition, withdrawal from the aquifers is sure to adversely affect the stream base flow and thus agricultural interests, wildlife habitat, and existing water rights allocations.

HYDROGEOLOGY OF TRACT C-a

General Setting

The following summary is taken largely from Tract C-a environmental baseline studies (RBOSP, 1977b). Tract C-a is in the western Piceance Basin, near the headwaters of Yellow Creek. The tract is at the head of the main valley of Corral Gulch, one of the two large tributaries of Yellow Creek, where the broad valley divides into several narrow valleys which have cut

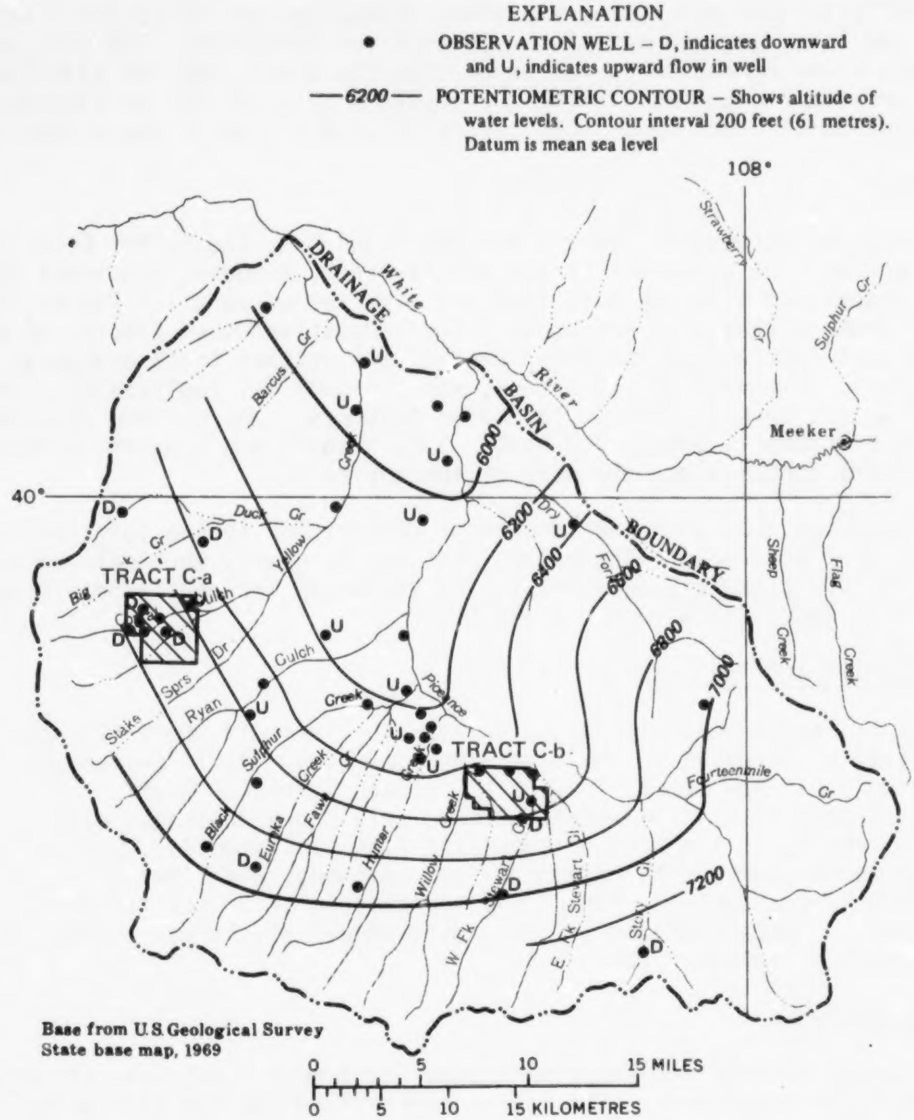

EXPLANATION
OBSERVATION WELL – D, indicates downward and U, indicates upward flow in well
6200 POTENTIOMETRIC CONTOUR – Shows altitude of water levels. Contour interval 200 feet (61 metres). Datum is mean sea level
108°
40°
DRAINAGE
BASIN
BOUNDARY
White River
Meeker
Strawberry Cr
Sulphur Cr
Sheep Creek
Flag Creek
TRACT C-a
TRACT C-b
Barcus Cr
Yellow Creek
Duck Cr
Big Gulch
Dry Gulch
Sprs
Stake
Ryan Gulch
Sulphur Creek
Black
Eureka
Fawn Cr
Hunter
Willow Creek
Piceance Creek
W. Fk. Stewart
E. Fk. Stewart Gl
Dry Fork
Fourteenmile Gr
Stewart Cr
6000
6200
6400
6600
6800
7000
7200
Base from U.S. Geological Survey State base map, 1969
0 5 10 15 MILES
0 5 10 15 KILOMETRES

Figure 5-5. Potentiometric map based on water levels in wells open to the Upper and Lower Aquifers, April 1974, Piceance Basin (Weeks et al., 1974).

upwards toward the Cathedral Bluff ridge. The tributaries of Corral Gulch, which flow east across the tract, unite at the east boundary. The flow of the main fork of Corral Gulch, up to the confluence with the Dry Fork, is broad and flat, but the rest of the canyons are V-shaped, with steep walls separated from adjacent canyons by rounded ridgetops. The elevation ranges from 6600 feet in Corral Gulch to 7400 feet on the western boundary.

Surficial outcrops within the tract boundaries belong to the Uinta Formation and intruding tongues of the Green River Formation. The main body of the Green River Formation is not exposed on the tract, but the Black Sulfur Tongue and another unnamed tongue are present. Figure 5-6, an east-west cross section of Tract C-a, shows the relative position of these features.

Structure

The major structural feature beneath Tract C-a, the Sulfur Creek Anticline, crosses the southwest corner of the tract, plunging southeast (Figure 5-7). Associated with the anticline are a series of parallel faults, in echelon from northwest to southeast. The largest and most complex of the fault groups cuts across the north part of the western tract boundary. This fault group, like most of the others, has two parallel faults with a down-dropped graben between them as its major features. The maximum displacement along this graben is 230 to 240 feet. Such grabens are apparently a result of tensional forces along the nose of the anticline.

Also associated with the structural deformation is the jointing and fracturing of the rocks. The major joint set is nearly vertical and oriented N50°-76°W, approximately parallel to the strike of the anticline. A secondary set strikes N28W, and a tertiary set N15W.

Precipitation and Drainage

The average annual precipitation over the tract is about 12 inches. Precipitation increases to the west with elevation. Table 5-1 compares precipitation at Yellow Creek, Tract C-a, and the Cathedral Bluffs to the west. Because of this fairly low precipitation, only those drainages with headwaters extending to the west of the tract flow consistently. Corral Gulch is the only water course with perennial flow, although Box Elder Gulch is fairly dependable in the spring. Figure 5-8 indicates most of the streamflow is derived from springtime snowmelt. Ths total annual discharges of the tract watersheds are listed in Table 5-2.

Springs and Seeps

Numerous springs and seeps have been found near Tract C-a, six within or near the tract boundaries. The source of the flow for the six springs marked in Figure 5-9 was identified by means of a comparison of spring elevation with the potentiometric of the Upper Aquifer (Method 1), a statistical analysis of spring flow (Method 2), and comparison of flow between different springs (Method 3) (Table 5-3).

Alluvial Aquifers

Some of the springs which supply flow in the perennial water courses [illegible] undoubtedly fed by the alluvial aquifers. Seven holes were drilled in al[illegible]vium on and near the tract in order to investigate these alluvial aquifers. Water was encountered in only four of the holes, along the main fork of Corral Gulch and Box Elder Gulch and Stake Springs Draw. The thickness of saturated alluvium ranged from 12 to 54 feet, averaging 27 feet. The locations of these

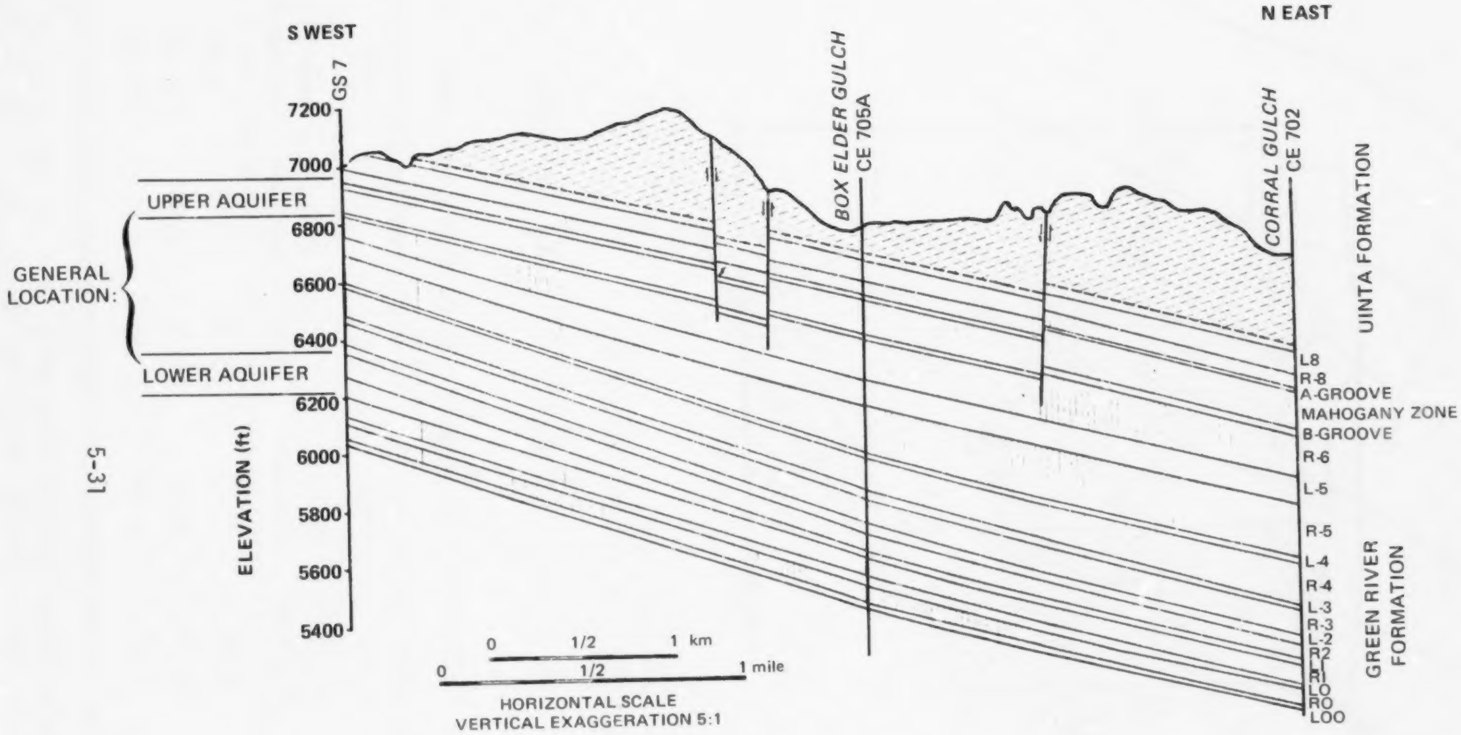

S WEST
N EAST
GS 7
BOX ELDER GULCH
CE 705A
CORRAL GULCH
CE 702
7200
7000
6800
6600
6400
6200
6000
5800
5600
5400
ELEVATION (ft)
GENERAL LOCATION:
UPPER AQUIFER
LOWER AQUIFER
UINTA FORMATION
L8
R-8
A-GROOVE
MAHOGANY ZONE
B-GROOVE
R-6
L-5
R-5
L-4
R-4
L-3
R-3
L-2
R2
L1
R1
LO
RO
LOO
GREEN RIVER FORMATION
0
1/2
1 km
0
1/2
1 mile
HORIZONTAL SCALE
VERTICAL EXAGGERATION 5:1

Figure 5-6. East-west geologic section through Tract C-a.

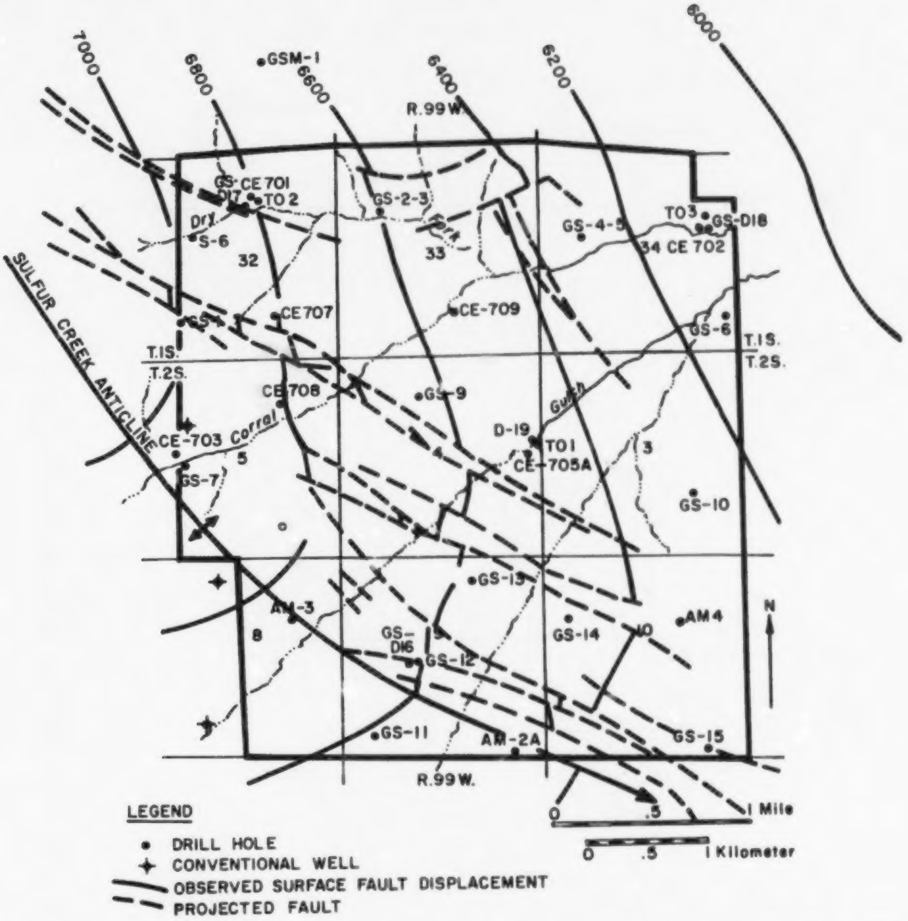

7000
6800
GSM-1
6600
6400
6200
6000
R.99W.
GS CE701
D17
TO 2
GS-2-3
Dry
S-6
32
Fork
33
GS-4-5
TO3
GS-D18
34 CE 702
SULFUR CREEK ANTICLINE
CE707
CE-709
GS-6
T.1S.
T.2S.
GS
T.1S.
T.2S.
CE 708
GS-9
Gulch
D-19
TO1
CE-705A
CE-703
Corral
5
3
GS-7
GS-10
GS-13
AM-3
8
AM4
GS-14
10
GS-D16
GS-12
GS-11
AM-2A
GS-15
R.99W.
N
LEGEND
DRILL HOLE
CONVENTIONAL WELL
OBSERVED SURFACE FAULT DISPLACEMENT
PROJECTED FAULT
0
.5
1 Mile
0
.5
1 Kilometer

Figure 5-7. Tract C-a middle A-groove structure map (RBOSP, 1977a).

TABLE 5-1. PRECIPITATION SUMMARY, WATER YEARS 1975 AND 1976

Location	1975 Monthly maximum	1975 Monthly minimum	1975 Total	1976 Monthly maximum	1976 Monthly minimum	1976 Total
Cathedral Bluffs	2.87	0.43	16.30	2.49	0.40	17.25
Tract C-a[a]	2.10	0.16	13.25	1.97	0.12	11.83
Yellow Creek	1.67	0.04	10.85	1.91	0.29	10.72

[a] 1975 values are from Stakes Springs Draw data; 1976 values represent the averages of Dry Fork, Corral Gulch, Box Elder Gulch, and Stake Springs Draw data.

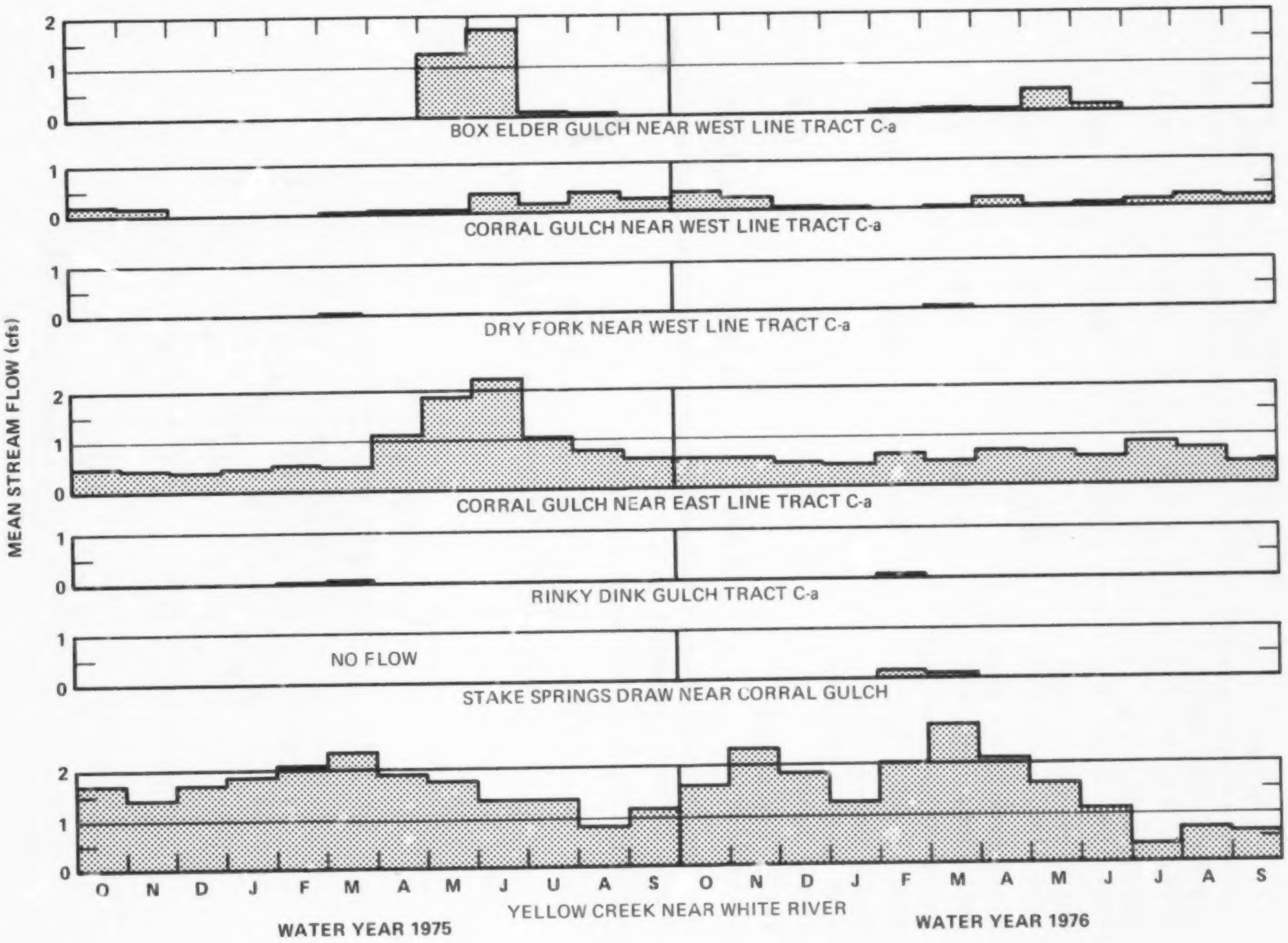


Figure 5-8. Monthly mean flows at seven gaging stations, water years 1975 and 1976 (RBOSP, 1977b).

TABLE 5-2. ANNUAL RUNOFF (acre-feet).

Station	Water year 1974[a]	Water year 1975	Water year 1976
Dry Fork near west line, Tract C-a	1.4	0.2	4.3
Corral Gulch near west line, Tract C-a	134.0	96.7	98.5
Box Elder Gulch near west line, Tract C-a	148.4	182.8	34.8
Rinky Dink Gulch near east line, Tract C-a	no data	0.6	2.3
Corral Gulch near east line, Tract C-a	309.3	626.2	418.1
Stake Springs Draw near confluence with Corral Gulch	0	0	15.5
Yellow Creek near White River	1,740[b]	1,158.7	1,103.1

[a] March through September only.

[b] Complete records for water year 1974.

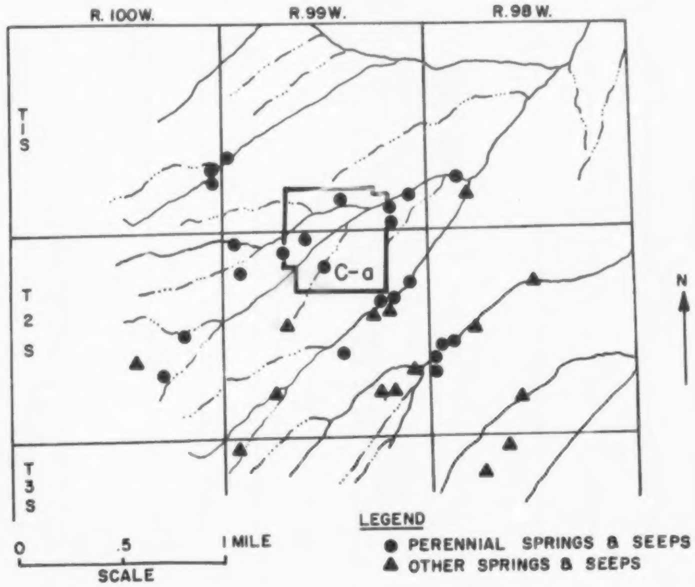

R. 100W.
R.99W.
R.98W.
T 1 S
T 2 S
T 3 S
C-a
N
0
.5
1 MILE
SCALE
LEGEND
● PERENNIAL SPRINGS & SEEPS
▲ OTHER SPRINGS & SEEPS

Figure 5-9. Springs and seeps in vicinity of Tract C-a (RBOSP, 1977b).

TABLE 5-3. SUGGESTED SOURCE OF SPRING WATER

Station	Method 1	Method 2	Method 3
1	Alluvial	Alluvial	Alluvial
2	Upper Aquifer	Alluvial	Alluvial and Upper Aquifer
3	Upper Aquifer	Upper Aquifer	Upper Aquifer
4	Upper Aquifer	Upper Aquifer	Upper Aquifer
5	Upper Aquifer	Upper Aquifer	Upper Aquifer
8	Upper Aquifer	Upper Aquifer	Upper Aquifer

holes are identified in Figure 5-10 and the data for them summarized in Table 5-4. That these alluvial aquifers are indeed closely related to the surface water of the region is strongly indicated by the comparison of aquifer water level and streamflow in Figure 5-11. The springtime rise in alluvial aquifer water levels is a response to infiltration of snowmelt.

Deep Aquifers

The configuration of the Upper and Lower Aquifers beneath Tract C-a is shown in Figures 5-12 and 5-13 (RBOSP, 1977b). The positions of the aquifers shown were located by means of open hole well flow charts which were constructed using spinner logs. These data indicate that, to a considerable extent, the aquifers are completely independent of lithology and stratigraphy. Aquifer tests on the Tract C-a wells established that the vertical permeability of the upper Mahogany Zone is exceedingly small (15×10^{-7} ft per day). Weeks et al. (1974) reported that in none of the many aquifer tests performed over the basin were they able to observe influence of pumping across the Mahogany Zone. Thus, to show the entire thickness of the Upper Aquifer varying from above the top of the Mahogany Zone to well below it seems unrealistic.

Spinner logs only respond to flow between layers of different head within a well. If the head difference is not significant, no flow will occur between even highly transmissive layers. Thus, Figures 5-12 and 5-13 probably more accurately reflect relative head differences within the aquifers than they do the locations of the most transmissive zones within the aquifers. Inasmuch as the well perforations were placed on the basis of this analysis, the wells may also not be representative of the aquifers, as defined on the basis of either transmissivity or water quality. The cross-sectional configuration of the aquifer is shown in Figure 5-6, with aquifer divisions indicated on the basis of stratigraphy rather than flow logs.

Upper Aquifer--

The potentiometric surface of the Upper Aquifer (RBOSP, 1977b) under Tract C-a shows an orientation fairly well in accordance with the regional

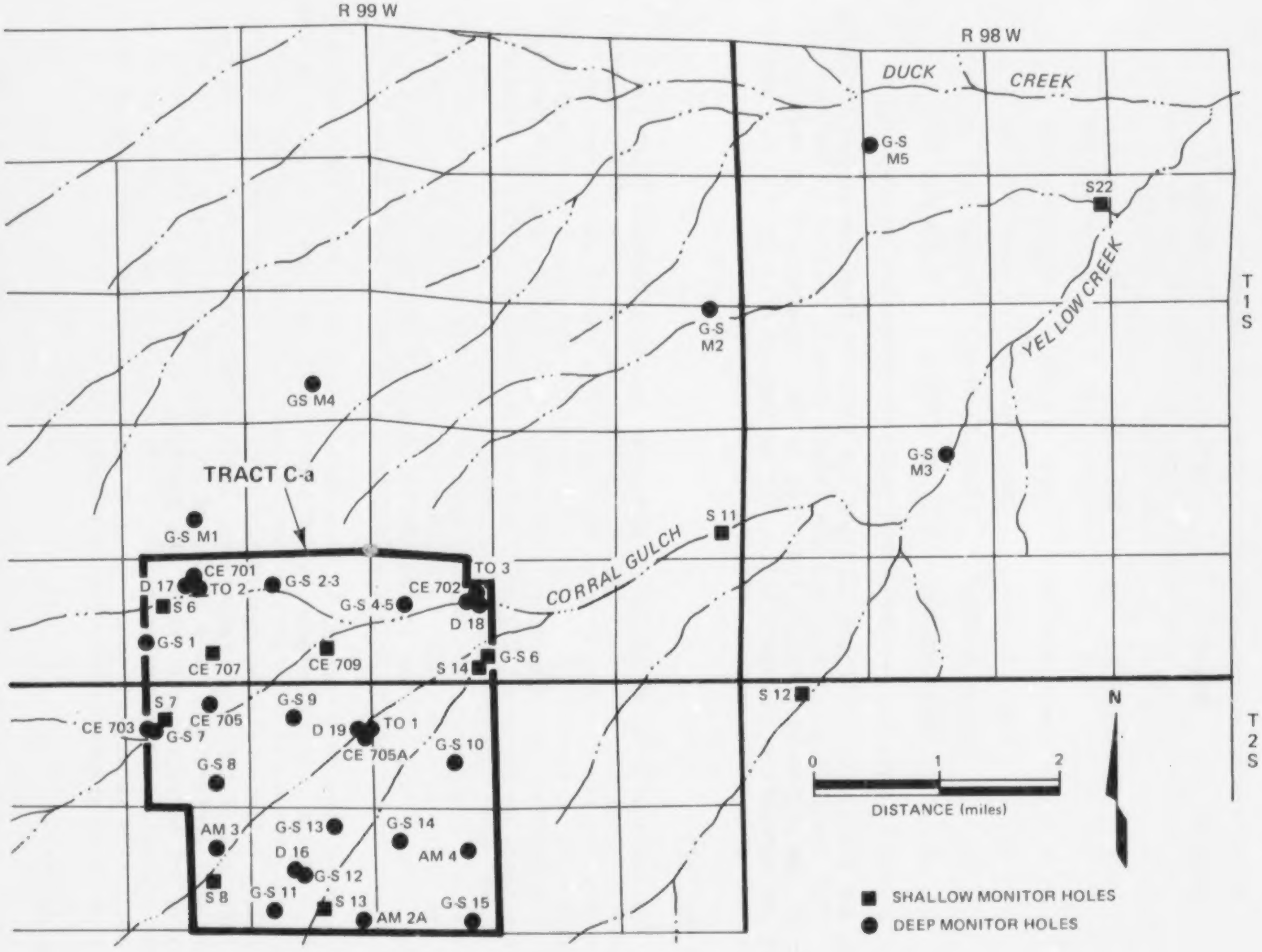

R 99 W
R 98 W
DUCK
CREEK
G-S M5
S22
YELLOW CREEK
T 1 S
G-S M2
GS M4
G-S M3
TRACT C-a
G-S M1
S 11
CORRAL GULCH
CE 701
TO 3
D 17
TO 2
G-S 2-3
CE 702
G-S 4-5
S 6
D 18
G-S 1
CE 707
CE 709
S 14
G-S 6
S 12
N
S 7
G-S 9
CE 705
TO 1
CE 703
D 19
G-S 7
CE 705A
G-S 10
T 2 S
G-S 8
0
1
2
DISTANCE (miles)
G-S 13
G-S 14
AM 3
D 16
AM 4
G-S 12
S 8
G-S 11
S 13
G-S 15
AM 2A
SHALLOW MONITOR HOLES
DEEP MONITOR HOLES

Figure 5-10. Tract C-a monitoring holes (RBOSP, 1976).

TABLE 5-4. SUMMARY OF ALLUVIAL MONITORING HOLES PHYSICAL DATA

Hole	Depth (feet)	Mean static water level (feet)	Standard deviation	Mean temperature (°F)	Standard deviation	Mean conductivity (μmhos)	Standard deviation[a]
G-S S-7	44	21.6[a]	2.5	48.6	2.9	1,096	58.0
G-S S-8	50	35.7[a]	3.7	49.2	2.9	970	83.3
G-S S-11	66	44.0	1.5	50.6	3.0	1,796	187.5
G-S S-12	87	32.6	1.5	49.7	5.3	1,596	135.9

[a] Geometric mean, standard deviation by method of movements.

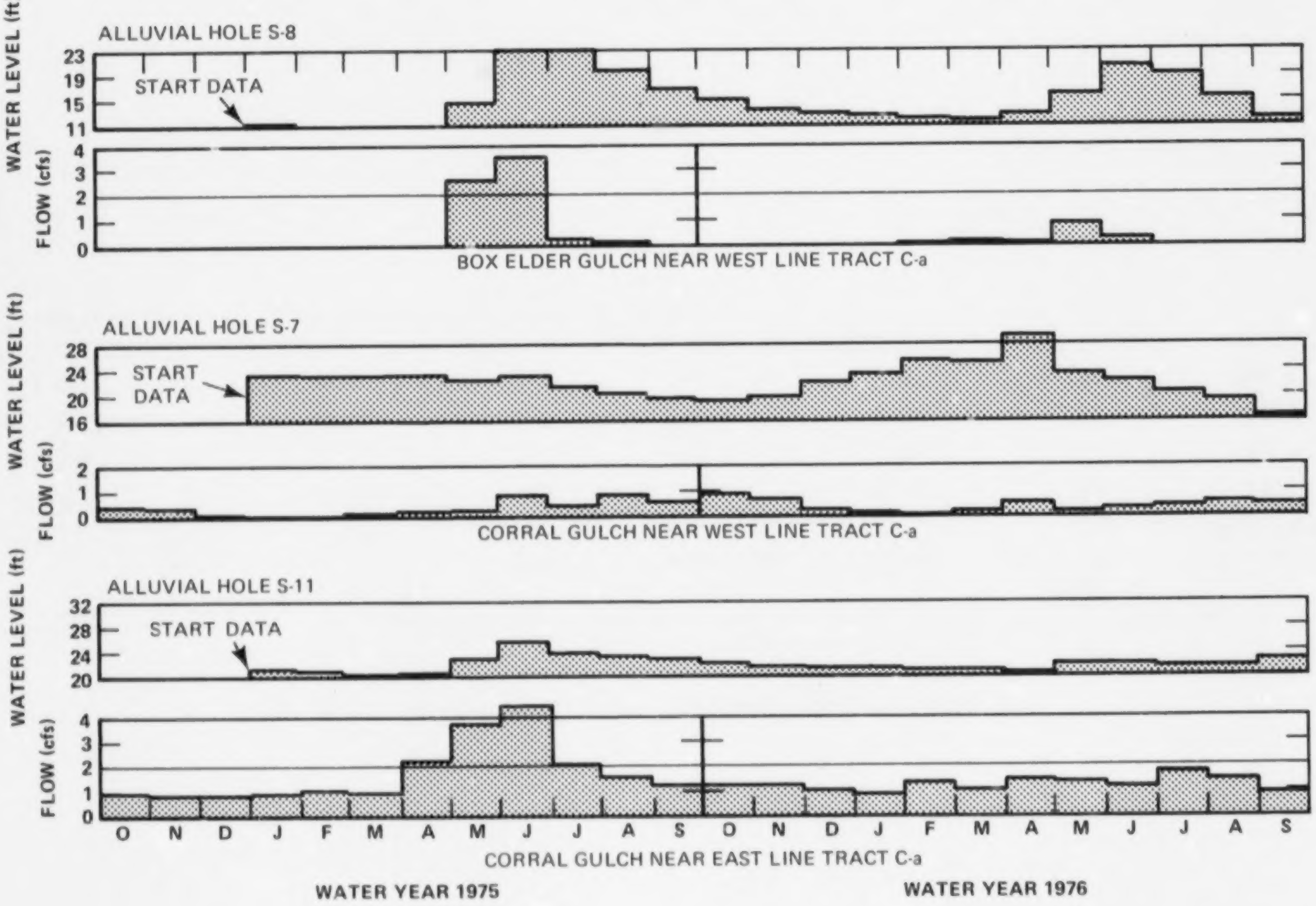


Figure 5-11. Alluvial hole water level versus streamflow (RBOSP, 1977b).

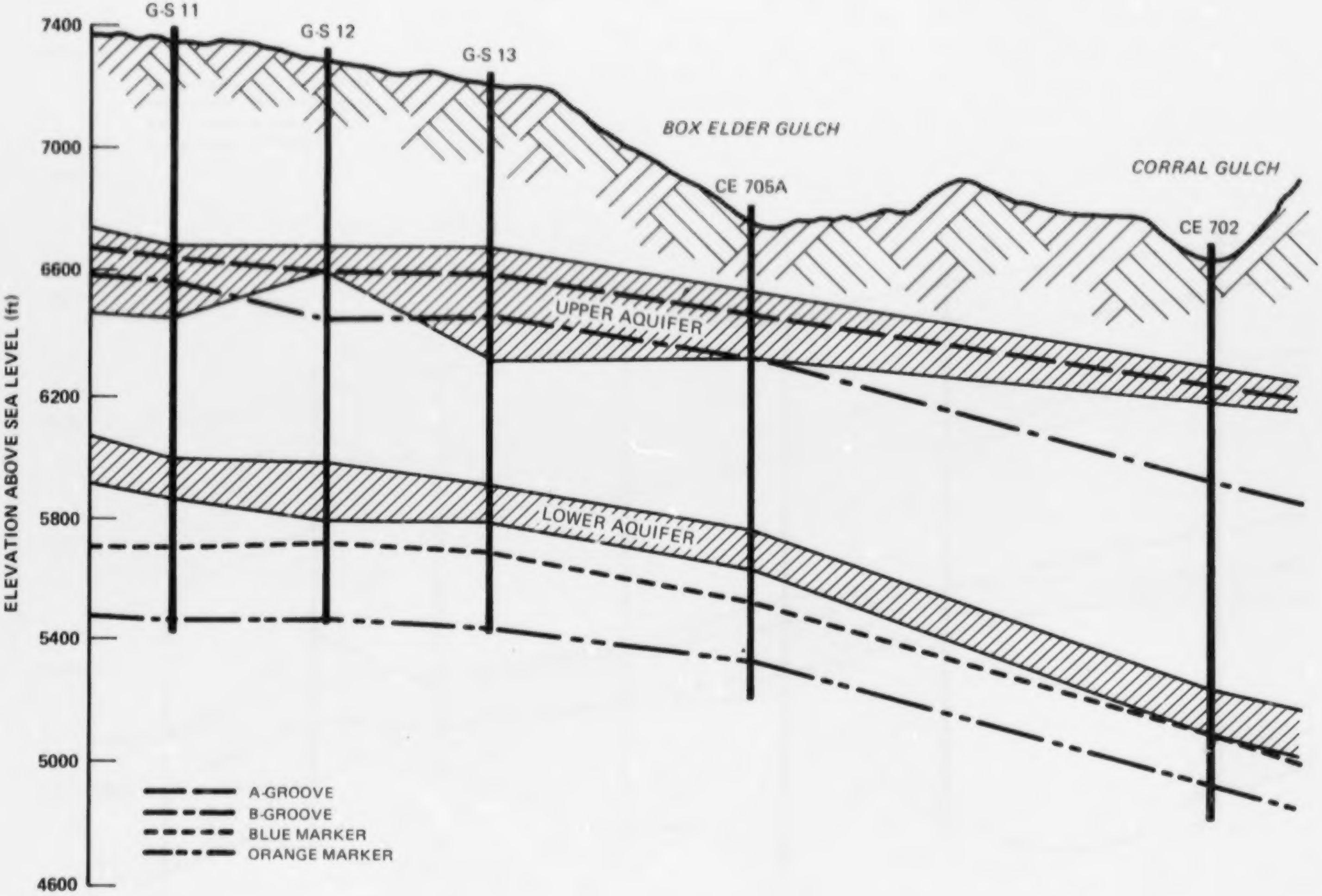

G-S 11
G-S 12
G-S 13
BOX ELDER GULCH
CE 705A
CORRAL GULCH
CE 702
UPPER AQUIFER
LOWER AQUIFER
7400
7000
6600
6200
5800
5400
5000
4600
ELEVATION ABOVE SEA LEVEL (ft)
A-GROOVE
B-GROOVE
BLUE MARKER
ORANGE MARKER

Figure 5-12. Cross section, Upper and Lower bedrock aquifer under Tract C-a (RBOSP, 1977b).

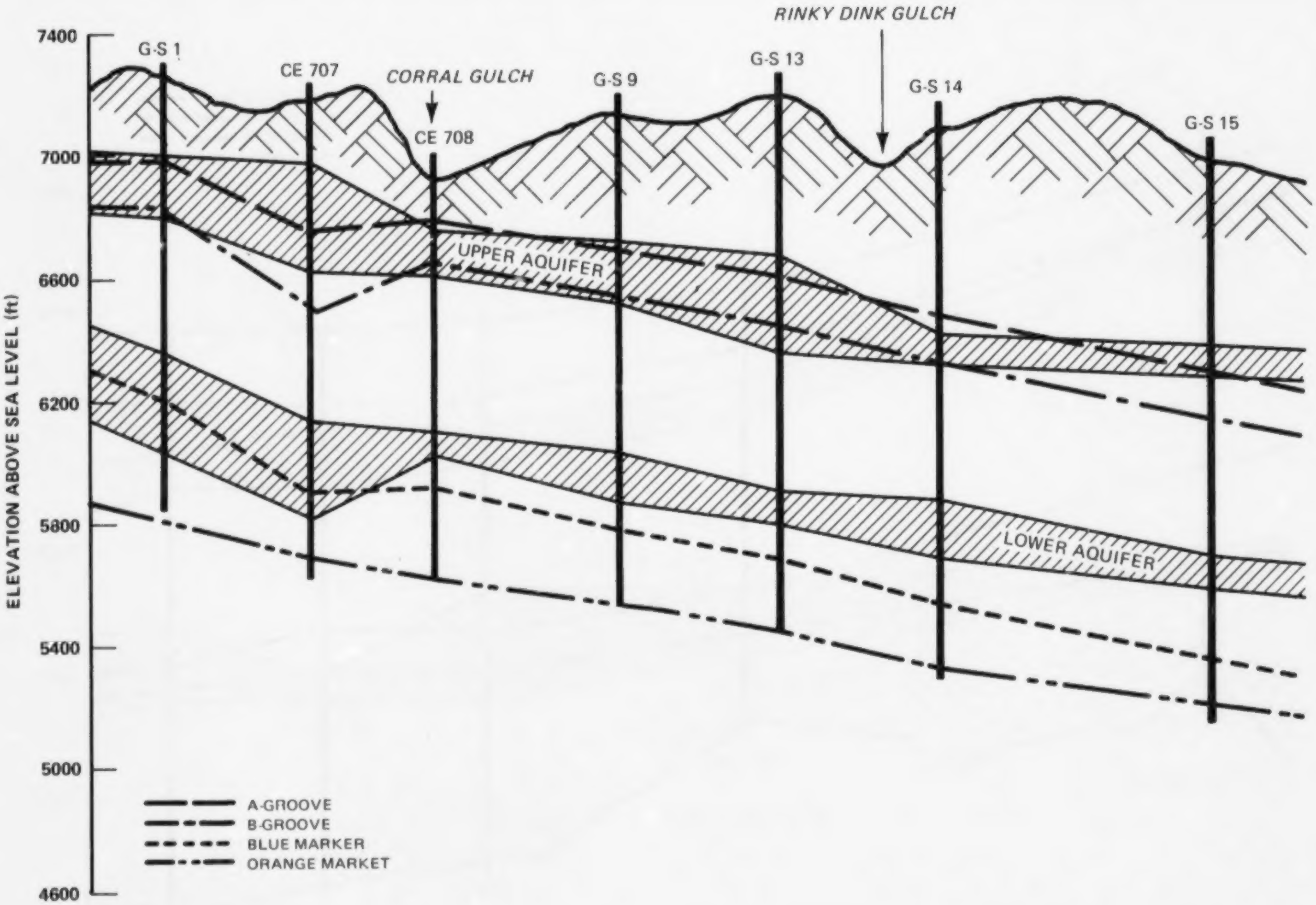

7400
7000
6600
6200
5800
5400
5000
4600
ELEVATION ABOVE SEA LEVEL (ft)
G-S 1
CE 707
CORRAL GULCH
CE 708
G-S 9
G-S 13
RINKY DINK GULCH
G-S 14
G-S 15
UPPER AQUIFER
LOWER AQUIFER
A-GROOVE
B-GROOVE
BLUE MARKER
ORANGE MARKET

Figure 5-13. Upper and Lower bedrock aquifers under Tract C-a (RBOSP, 1977b).

model presented in Weeks et al. (1974), although the gradient is somewhat steeper across the tract. The Weeks model shows the 7000-foot head line several miles farther west than does Figure 5-14. The gradient in Figure 5-14 is about 130 feet per mile. The potentiometric map shows little evidence of either recharge or discharge in the vicinity of the tract.

Upper Aquifer hydraulic parameters were determined through a large number of short (informal) aquifer tests and one long (formal) test (RBOSP, 1977b). The average transmissivity reported was 2040 ft^2 per day and the average storage coefficient was 6.8×10^{-5}. This transmissivity is high in comparison to the values reported by Weeks et al., which were on the order of perhaps 130 to 270 ft^2 per day. It appears that the high T values obtained may be the result of pumping only long enough to reach the relatively flat middle limb of the typical semi-log fractured aquifer drawdown curve. For this report, drawdown and recovery curves were not obtained or available for all of the tests on Tract C-a, and those which were obtained did not contain information necessary for complete analysis. Several shortcomings were noted. Tests tended to be too short, measurements during recovery were not carried out for a long enough period, and incorrect recovery measurements were used. Without more information, no definitive model of the aquifer characteristics can be constructed.

Area-wide water-level change data were used to overcome aquifer test inadequacies. Eleven wells on the tract were open to both aquifers for two years after drilling. An estimated 50 gallons per minute flowed from the Upper to the Lower Aquifer. After 2 years, the aquifer interconnection was cut off and water levels in the Upper Aquifer began to recover. A Theis-type interference model was constructed to simulate recovery data. Calibration of the model showed that the use of a transmissivity of 400 ft^2 per day and a storage coefficient of 10^{-3} best produced the recovery data.

Upper Aquifer test drawdown cones for wells G-S 12 and CE 705A are illustrated in Figures 5-15 and 5-16, respectively. The influence of faulting on the Upper Aquifer is clear. The potentiometric surface map of Figure 5-14 is reconstructed in Figure 5-17 to show the influence of faults as no-flow boundaries.

The elliptical shape of the drawdown cone in Figure 5-16 indicates a strongly anisotropic aquifer. Utilizing the principle that $T_{max} = (a/b)T_e$ (where a equals the major axis of the drawdown ellipse, b equals the minor axis, and T_e is the effective transmissivity), and $T_{min} = (b/a)T_e$, T_{max} equals 2.9 T_e, and T_{min} equals 0.35 T_e. If T_e is 400 ft^2 per day, T_{max} is 1160 ft^2 per day and T_{min} is 140 ft^2 per day. The ratio $T_{max}:T_{min}$ is 8.3:1. T_{max} is oriented N23W, slightly east of what would be expected from the joint and fracture orientations given.

Such major anisotropy should cause a significant divergence of the flow pattern from what would be expected if the aquifer were isotropic. Figure 5-18 is an anisotropic flow net of the Upper Aquifer below Tract C-a, constructed by means of an anisotropic flow net transform. This flow net does not attempt to include the effects of the faults individually, as presented in Figure 5-17, but is based on Figure 5-14, an "averaged" approximation of

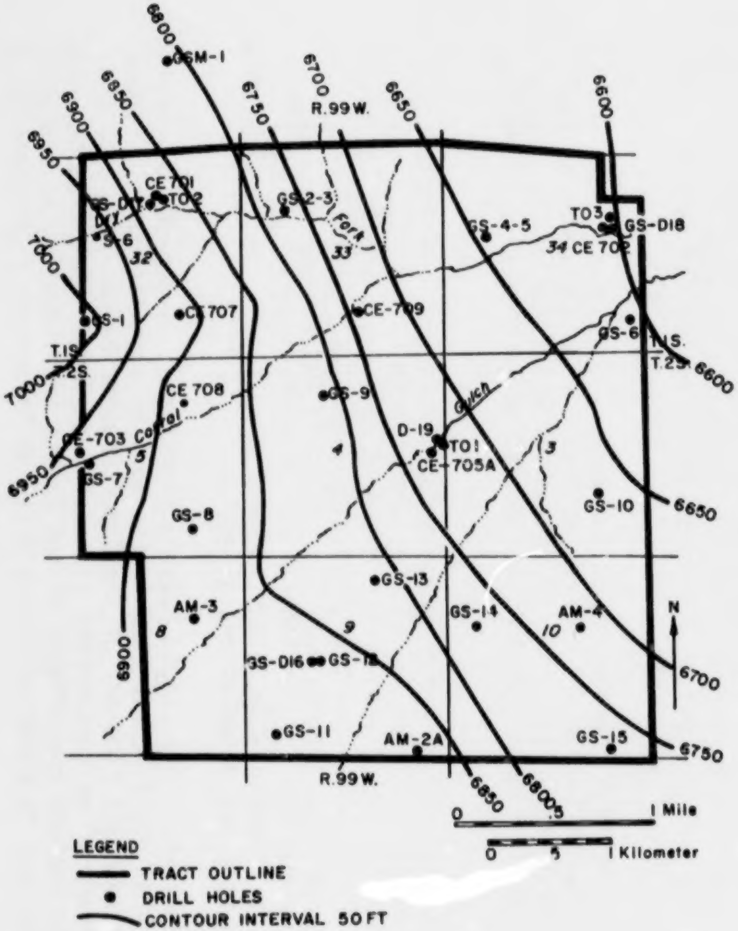

GSM-1
R.99W.
6600
6650
6700
6750
6800
6850
6900
6950
7000
T.1S.
T.2S.
CE 701
GS-D17
TO 2
GS-2-3
GS-4-5
TO3
GS-D18
CE 702
S-6
32
33
34
Dry
Fork
GS-1
CE 707
CE-709
GS-6
CE 708
GS-9
Gulch
D-19
TO1
CE-705A
CE-703
Corral
GS-7
5
4
3
GS-8
GS-10
GS-13
AM-3
GS-14
AM-4
8
9
10
GS-D16
GS-12
GS-11
AM-2A
GS-15
R.99W.
N
0
.5
1 Mile
1 Kilometer
LEGEND
TRACT OUTLINE
DRILL HOLES
CONTOUR INTERVAL 50 FT

Figure 5-14. Upper Aquifer piezometric levels (feet), Tract C-a, November 1975 (RBOSP, 1976).

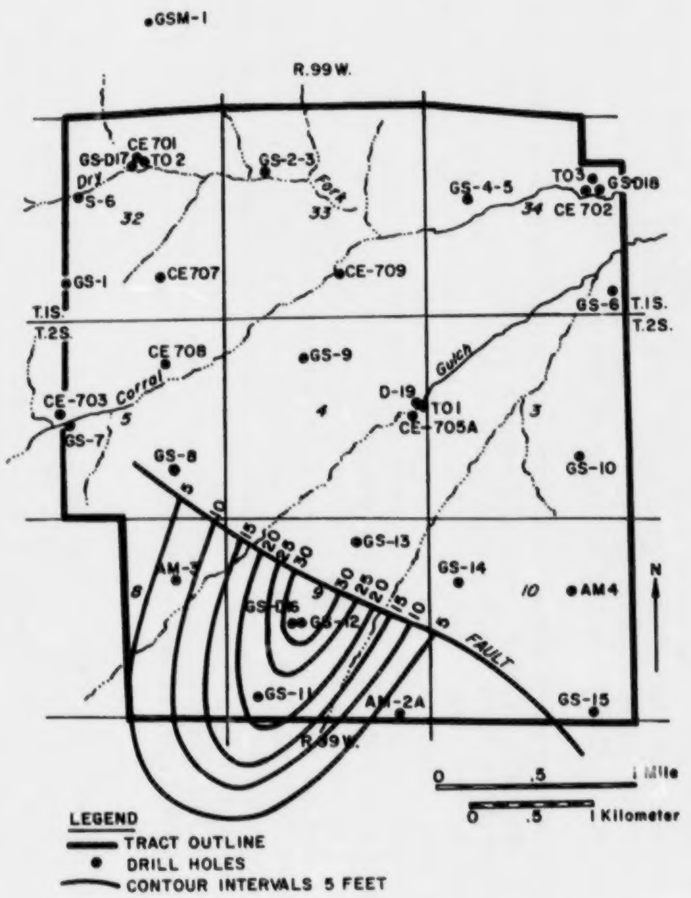

GSM-1
R.99W.
CE 701
GS-D17
TO 2
GS-2-3
GS-4-5
TO3
GS-D18
CE 702
Dry
Fork
S-6
32
33
34
GS-1
CE 707
CE-709
GS-6
T.1S.
T.2S.
CE 708
GS-9
D-19
Gulch
TO1
CE-705A
CE-703
Corral
GS-7
5
4
3
GS-8
GS-10
GS-13
AM-3
GS-14
AM4
8
9
10
GS-D16
GS-12
FAULT
GS-11
AM-2A
GS-15
R.99W.
N
0
.5
1 Mile
1 Kilometer
LEGEND
TRACT OUTLINE
DRILL HOLES
CONTOUR INTERVALS 5 FEET

Figure 5-15. Upper Aquifer test drawdown G-S 12 at approximately 13,000 minutes after test start, Tract C-a (RBOSP, 1977b).

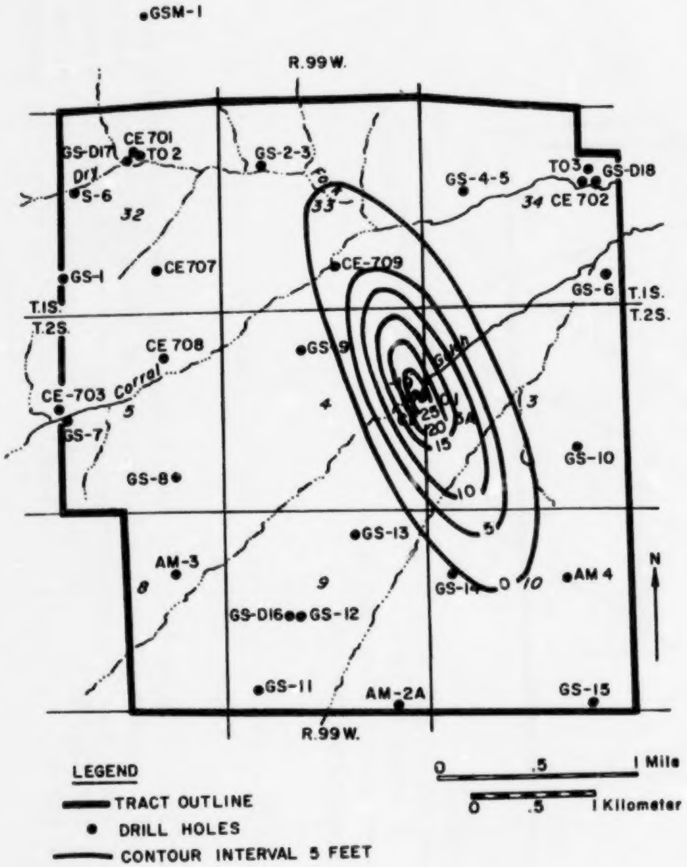

GSM-1
R.99W.
GS-D17
CE 701
TO 2
Dry
S-6
32
GS-2-3
Fork
33
GS-4-5
TO3
GS-D18
34 CE 702
GS-1
CE707
CE-709
GS-6
T.1S.
T.2S.
CE 708
GS-9
Gulch
CE-703 Corral
5
4
25
20
15
10
5
3
GS-7
GS-8
GS-10
GS-13
AM-3
8
9
GS-14
0
10
AM 4
N
GS-D16
GS-12
GS-11
AM-2A
GS-15
R.99W.
0 .5 1 Mile
0 .5 1 Kilometer
LEGEND
TRACT OUTLINE
DRILL HOLES
CONTOUR INTERVAL 5 FEET

Figure 5-16. Upper Aquifer test cone of depression, Tract C-a (RBOSP, 1977b).

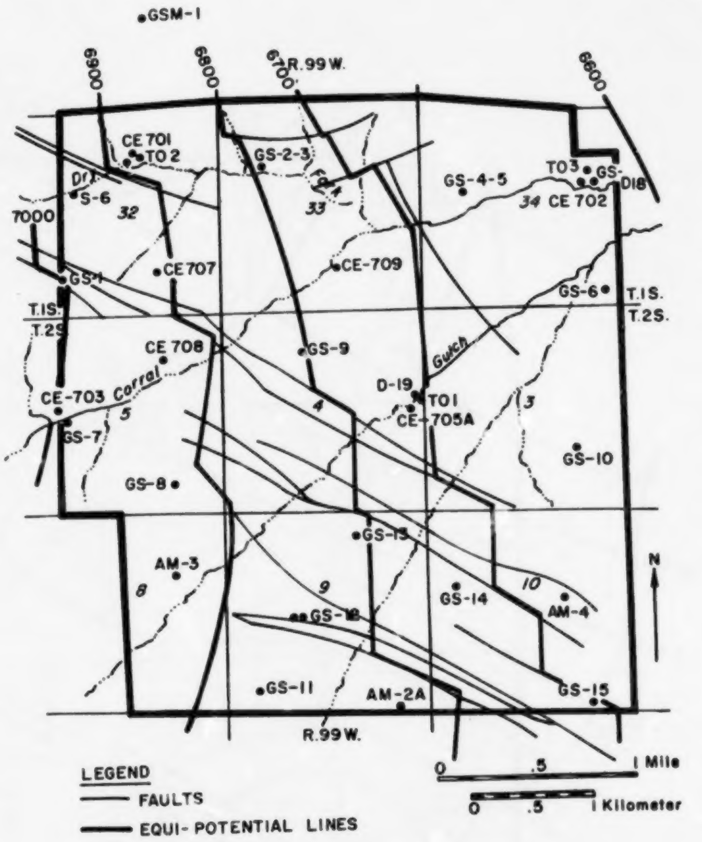

GSM-1
6900
6800
6700
R.99W.
6600
CE 701
TO 2
Dry
S-6
32
GS-2-3
Fork
33
GS-4-5
TO3
GS-D18
34 CE 702
7000
GS-1
CE707
CE-709
GS-6
T.1S.
T.2S.
CE 708
GS-9
Gulch
D-19
TO1
CE-705A
CE-703 Corral
5
4
3
GS-7
GS-8
GS-10
GS-13
AM-3
8
9
GS-14
10
AM-4
N
GS-12
GS-11
AM-2A
GS-15
R.99W.
0 .5 1 Mile
0 .5 1 Kilometer
LEGEND
FAULTS
EQUI-POTENTIAL LINES

Figure 5-17. Potentiometric surface for Upper Aquifer reconstructed from Figure 5-14 to show influence of faults on Tract C-a (RBOSP 1977b).

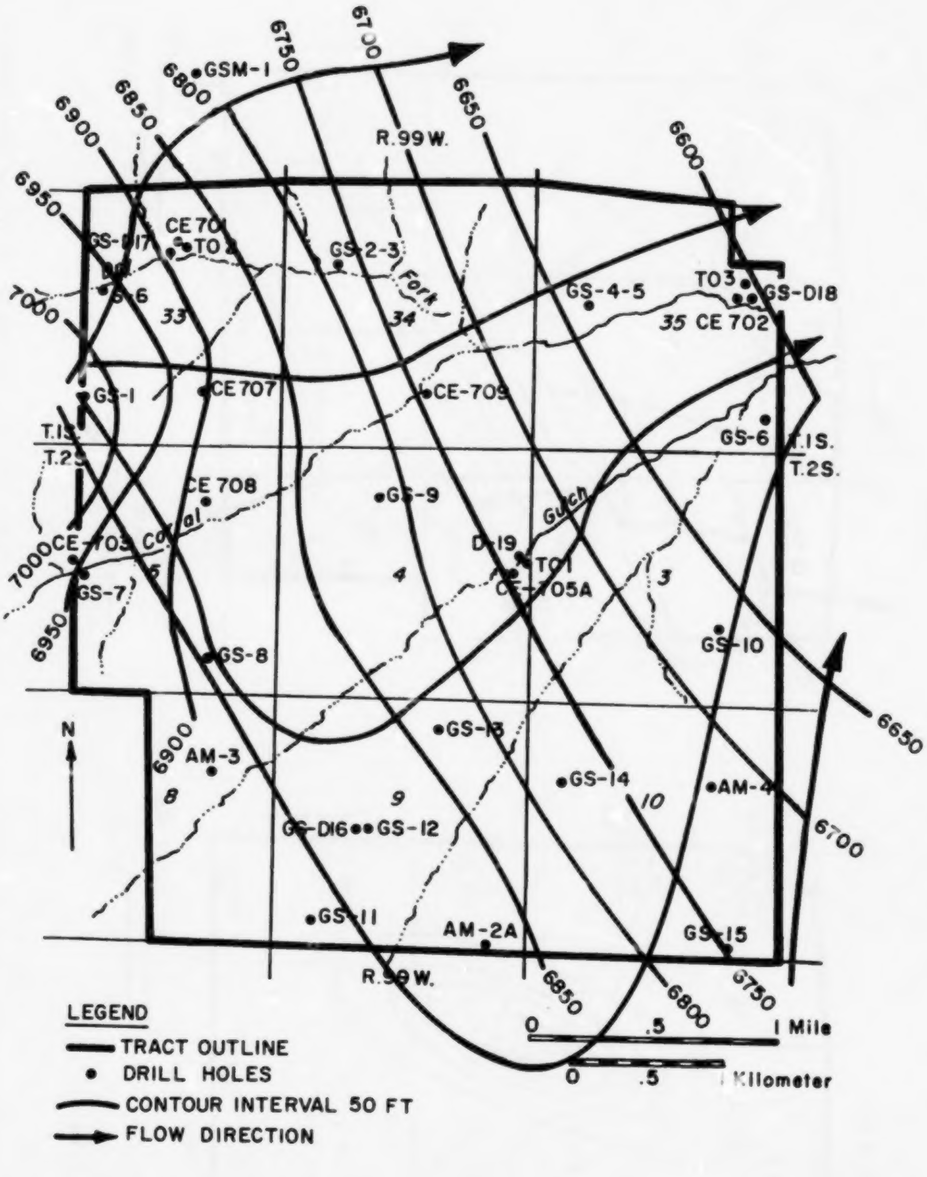

6800
GSM-1
6750
6700
6900
6850
6650
R.99 W.
6600
6950
CE 701
TO 2
GS-D17
GS-2-3
Fork
T03
GS-D18
7000
GS-6
33
34
GS-4-5
35 CE 702
GS-1
CE707
CE-709
T.1S.
T.2S.
GS-6
T.1S.
T.2S.
CE 708
GS-9
Gulch
Corral
7000
CE-703
D-19
TO1
CE-705A
GS-7
5
4
3
6950
GS-8
GS-10
N
6900
AM-3
GS-13
6650
8
9
GS-14
10
AM-4
GS-D16
GS-12
6700
GS-11
AM-2A
GS-15
R.99 W.
6850
6800
6750
LEGEND
TRACT OUTLINE
DRILL HOLES
CONTOUR INTERVAL 50 FT
FLOW DIRECTION
0
.5
1 Mile
0
.5
1 Kilometer

Figure 5-18. Anisotropic flow net for Upper Aquifer on Tract C-a (RBOSP, 1977b).

the actual surface. Figure 5-18 is, therefore, not exact and should be taken to represent only a generalized simplification of the actual flow. Any errors in the original map are exaggerated during the transformation process. In particular, the source of flow is probably not concentrated in the northwest corner of the tract, but is more evenly distributed along the western boundary.

Lower Aquifer--

The map of the potentiometric surface of the Lower Aquifer is shown in Figure 5-19. The small contour interval of this map is somewhat misleading. It is unlikely that the local flow is almost directly opposite the regional gradient, as the contours near the bottom of the tract would indicate. The gradients depicted on the southeast section of the map are on the order of 10 feet per mile or even less. These differences may well be as much the result of different intervals of perforation as of areal changes of head. If the

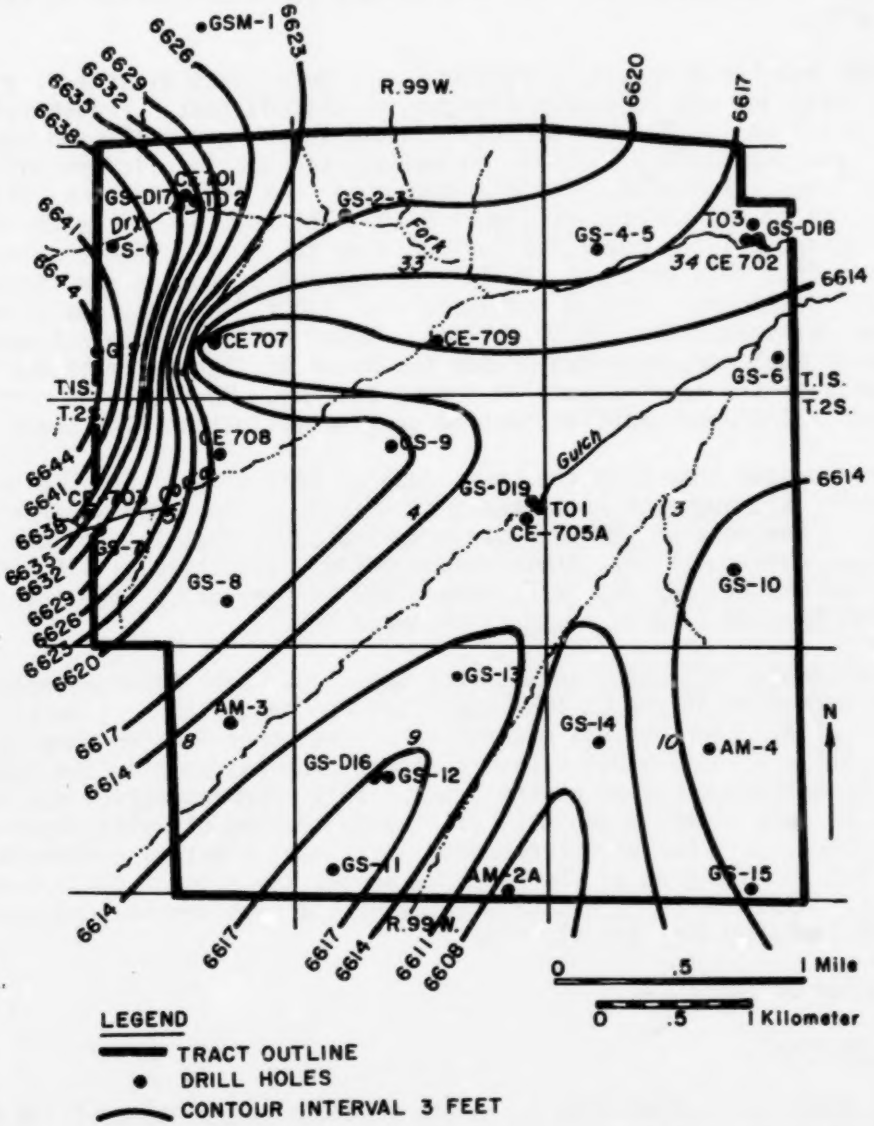

GSM-1
6626
6623
6629
6632
6635
6638
R.99W.
6620
6617
CE 701
GS-D17
TO 2
Dry
S-
GS-2-3
Fork
33
GS-4-5
TO3
GS-D18
34 CE 702
6641
6644
6614
CE707
CE-709
GS-6
T.1S.
T.2S.
CE 708
GS-9
Gulch
6644
6641
6638
CE-703
6635
6632
6629
6626
6623
6620
GS-7
GS-D19
TO1
CE-705A
3
4
GS-8
GS-10
GS-13
AM-3
GS-14
N
9
10
AM-4
8
GS-D16
GS-12
6617
6614
GS-11
AM-2A
GS-15
R.99W.
6614
6617
6617
6614
6611
6608
0
.5
1 Mile
0
.5
1 Kilometer
LEGEND
TRACT OUTLINE
DRILL HOLES
CONTOUR INTERVAL 3 FEET

Figure 5-19. Lower Aquifer piezometric levels (feet), Tract C-a, November 20, 1975 (RBOSP, 1977b).

smaller anomalies are overlooked, the Lower Aquifer map shows several significant differences from the Upper Aquifer map. The much flatter gradient in the Lower Aquifer (10 feet per mile across the tract compared to 130 feet per mile) is striking. This difference is probably at least partly a result of the much higher transmissivity of the Lower Aquifer. Another major influence is the fact that the Upper Aquifer discharges directly into Yellow and Piceance Creeks, while the Lower Aquifer must discharge by upward leakage to the Upper Aquifer. This slow, diffuse discharge over a large area should result in a region near the center of the basin over which the gradient is nearly flat. The middle of Tract C-a appears to be the border of this discharge area.

Lower Aquifer hydraulic parameters were determined by several short-term pumping tests and one long-term (length not stated) test. Transmissivity values ranged up to 2270 ft^2 per day for the short-term tests and averaged 1280 ft^2 per day (RBOSP, 1977b). An average storage coefficient value of 2.0×10^{-4} was calculated. The drawdown cone from the long-term test at well G-S D15 is illustrated in Figure 5-20. The test was of sufficient duration to affect all the Lower Aquifer wells on the tract. The transmissivity calculated from this test was 870 ft^2 per day and a storage coefficient of 1.2×10^{-4} was found. It was concluded that 930 ft^2 per day was a representative transmissivity (RBOSP, 1977b). RBOSP considered this transmissivity value to be much more dependable than the Upper Aquifer estimate due to the larger area of the aquifer sampled during pumping. However, the problems mentioned in the Upper Aquifer testing program evaluation also apply here.

The drawdown cone from the Lower Aquifer test of well G-S D16 is clearly anisotropic, although not as markedly as that from the Upper Aquifer well CE 705A test. Analysis of the drawdown cone indicates that T_{max} equals 1.45 T_e and T_{min} equals 0.17 T_e, these values being, respectively, 1350 ft^2 per day and 640 ft^2 per day if T_e equals 930 ft^2 per day. The ratio of T_{max} to T_{min} is 2 to 1. T_{max} is oriented N11W.

No evidence of leakage between the Upper and Lower Aquifers was found, with the exception of the CE 705A Upper Aquifer test. Here, a vertical permeability of 3.3 feet per day was derived. The Lower Aquifer pumping tests at wells G-S D18 and G-S D19 caused a significant response in the Upper Aquifer at the northeast corner of the tract. This interconnection may result from one or more of three causes: (1) faulty sealing of wells penetrating both aquifers, (2) fractures created by artificial fracturing experiments carried out in this area by the Water Resources Division of the U.S. Geological Survey (USGS) in 1973, and (3) faults with a high vertical permeability along the fault (RBOSP, 1977b).

HYDROGEOLOGY OF TRACT C-b

General Setting

Oil Shale Lease Tract C-b is in the southeastern portion of the Piceance Basin, just south of Piceance Creek. The tract is on the upland above the Piceance Creek Valley. The tract surface slopes gently upward to the south and is dissected by several narrow, straight stream valleys and gulches. The

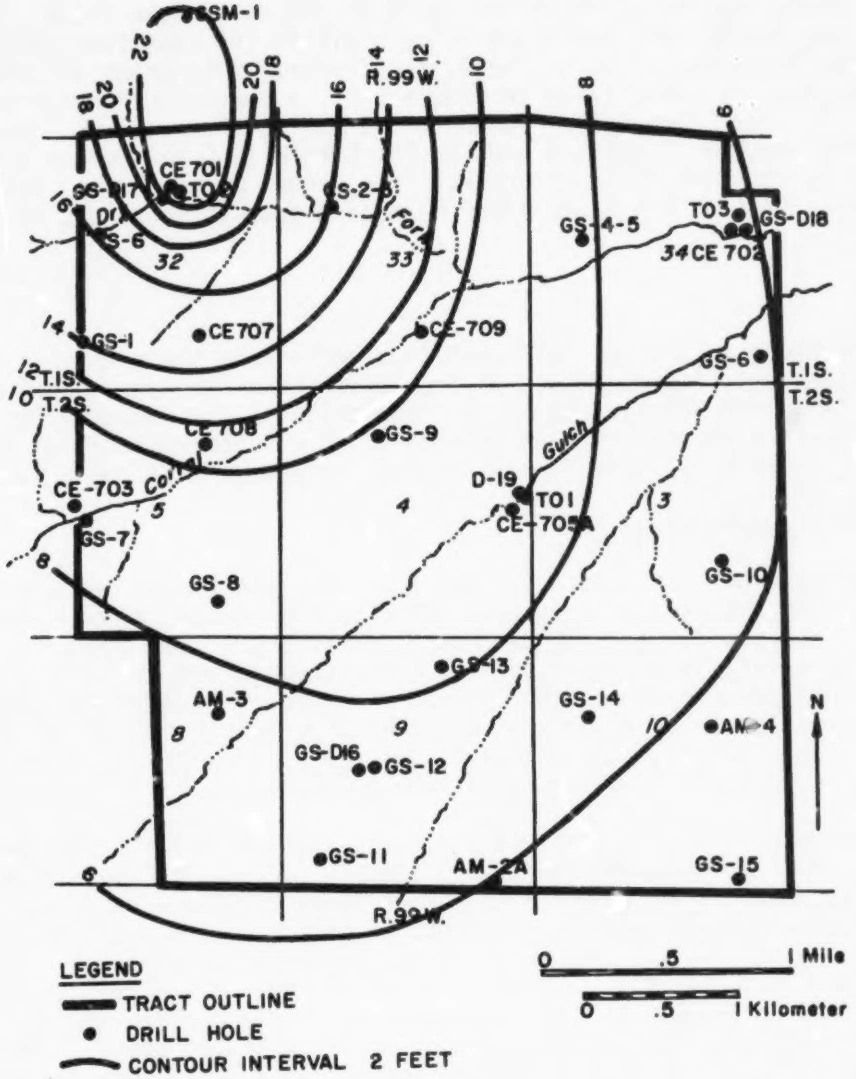

GSM-1
22
20
18
20
18
16
14
12
R.99W.
10
8
6
CE701
GS-D17
TO2
GS-2-3
16
Dr.
GS-6
32
Fork
33
GS-4-5
TO3
GS-D18
34
CE702
14
GS-1
CE707
CE-709
12
T.1S.
T.2S.
10
GS-6
T.1S.
T.2S.
CE708
GS-9
Gulch
D-19
TO1
CE-703
Corral
5
4
CE-705A
3
GS-7
8
GS-10
GS-8
GS-13
AM-3
GS-14
N
8
9
10
AM-4
GS-D16
GS-12
GS-11
AM-2A
GS-15
6
R.99W.
LEGEND
TRACT OUTLINE
DRILL HOLE
CONTOUR INTERVAL 2 FEET
0 .5 1 Mile
0 .5 1 Kilometer

Figure 5-20. Lower Aquifer test cone of depression (RBOSP, 1977b).

chief of these, Willow Creek and Stewart Gulch, bound the tract on the west and east, respectively. The canyon walls are steep but not rugged and the intervening ridges are broad and rounded. The elevation ranges from 6400 feet in Stewart and Willow Gulches, to 7100 feet at the south boundary.

All of the rock cropping out on the tract belongs to the Uinta Formation. The Uinta Formation in the Piceance Basin contains numerous tongues of the Green River Formation. As the ancient Green River Lake regressed toward the south in the mid-Eocene, floodplain sands and muds advanced to cover the lake sediments. However, repeated short-lived transgressions of the lake deposited clays and marls far to the north of the usual lake shore. These deposits have become thin marlstone tongues within the sandstone and mudstone of the Uinta Formation. Two of these, the Thirteen Mile Creek and the Black Sulfur Tongues, are illustrated in Figure 5-21, a north-south cross section of Tract C-b. The Black Sulfur Tongue crops out on the walls of Piceance Creek to the north of Tract C-b and the Thirteen Mile Creek tongue crops out several miles north of Piceance Creek. This tongue merges in the subsurface with the main body of the Green River Formation just to the south of Tract C-b.

Structure

The northern portion of the tract is underlain by the axis of a west plunging syncline. The curvature of the syncline is open and gentle and the plunge is less than 100 feet per mile. The depth of the Mahogany Zone depends more upon surface topography than structure. The depth varies from 1000 to 1300 feet (Figure 5-21). No faults or dikes were mapped on the tracts.

Precipitation and Drainage

The average precipitation over the tract is 12.4 inches per year. Precipitation does not vary greatly from place to place because the elevation differences are small. Most of the runoff passing over the tract does not originate from local precipitation, but from snowmelt and rainfall on the higher Roan Plateau to the south. The only canyons with dependable flow are Stewart and Willow Gulches, both of which have an annual average flow of about 2 cubic feet per second (1450 acre-feet per year). The discharge of Stewart Gulch is more constant than that of Willow Gulch.

Discharge of tract streams and Piceance Creek was observed to decline during the baseline study period (C-b Shale Oil Venture, 1977b). However, this decline seems to be a return to normal flows after a sudden peak in 1973 (Figure 5-22). One suggested explanation is that this peak was due to the Rio Blanco project nuclear explosion on May 17, 1973 (C-b Shale Oil Venture, 1977b). In an unsuccessful attempt to stimulate natural gas production in the tight Fort Union and Mesa Verde Formations, three nuclear explosions with a combined explosive force of 90,000 tons of TNT were detonated. Some formerly dry springs in the area were observed to renew flow. One and one-half hours after the similar Rulison project blast near Grand Valley, Colorado, the flow in nearby Battlement Creek tripled. A double mass curve analysis of White River above and below Piceance Creek (Figure 5-23) indicates that weather or climatic factors are not responsible. Thus, the peak in Piceance Creek flow and subsequent decline may well be related to the Rio Blanco explosion.

Springs and Seeps

No springs or seeps were found within the tract boundaries, but nine were found within less than 2 miles from the tract boundaries (Figure 5-24). Most of these were small, intermittent seeps, but several had discharges of 1 cubic foot per second or more. The discharges of most of the gaged springs (Figure 5-25) are quite constant, with the exception of spring S-10, which

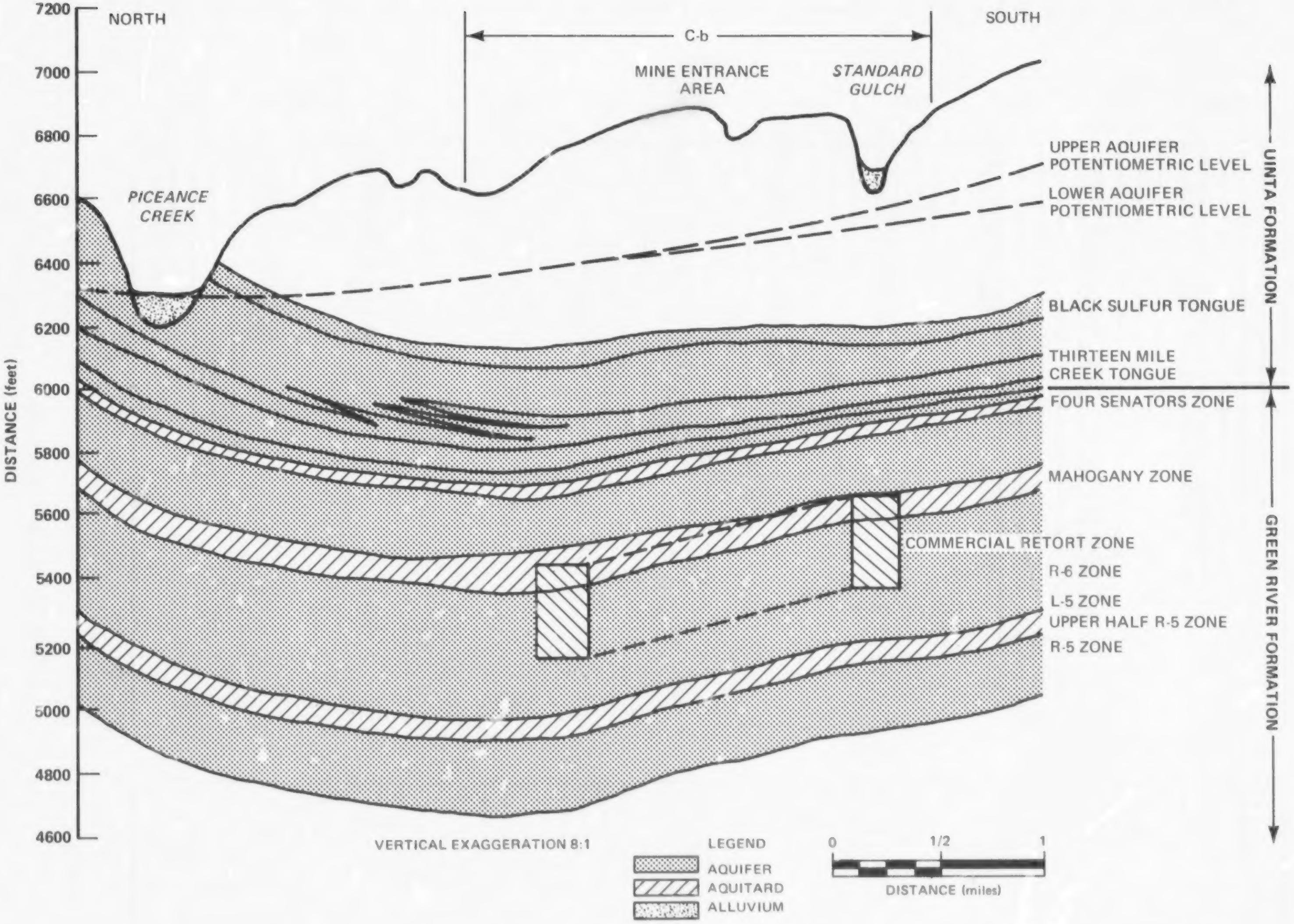

7200
7000
6800
6600
6400
6200
6000
5800
5600
5400
5200
5000
4800
4600
DISTANCE (feet)
NORTH
SOUTH
C-b
MINE ENTRANCE AREA
STANDARD GULCH
PICEANCE CREEK
UPPER AQUIFER POTENTIOMETRIC LEVEL
LOWER AQUIFER POTENTIOMETRIC LEVEL
BLACK SULFUR TONGUE
THIRTEEN MILE CREEK TONGUE
FOUR SENATORS ZONE
MAHOGANY ZONE
COMMERCIAL RETORT ZONE
R-6 ZONE
L-5 ZONE
UPPER HALF R-5 ZONE
R-5 ZONE
UINTA FORMATION
GREEN RIVER FORMATION
VERTICAL EXAGGERATION 8:1
LEGEND
AQUIFER
AQUITARD
ALLUVIUM
0
1/2
1
DISTANCE (miles)

Figure 5-21. North-south geologic cross section of Tract C-b (C-b Shale Oil Venture, 1977b).

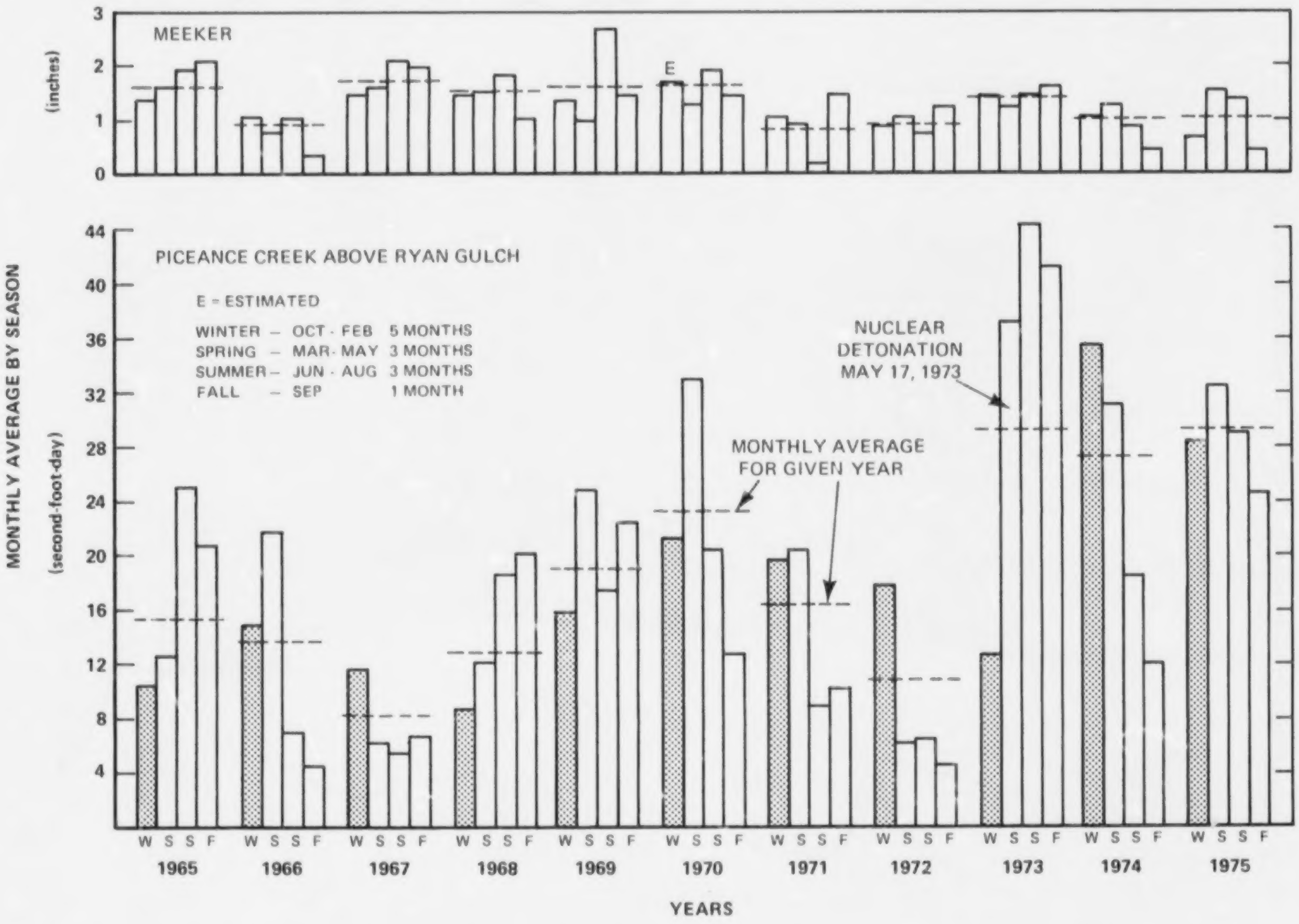


Figure 5-22. Monthly averages by season for streamflow at Piceance Creek above Ryan Gulch, USGS 09306200, and for precipitation at Meeker, 1965-1975 (C-b Shale Oil Venture, 1977b).

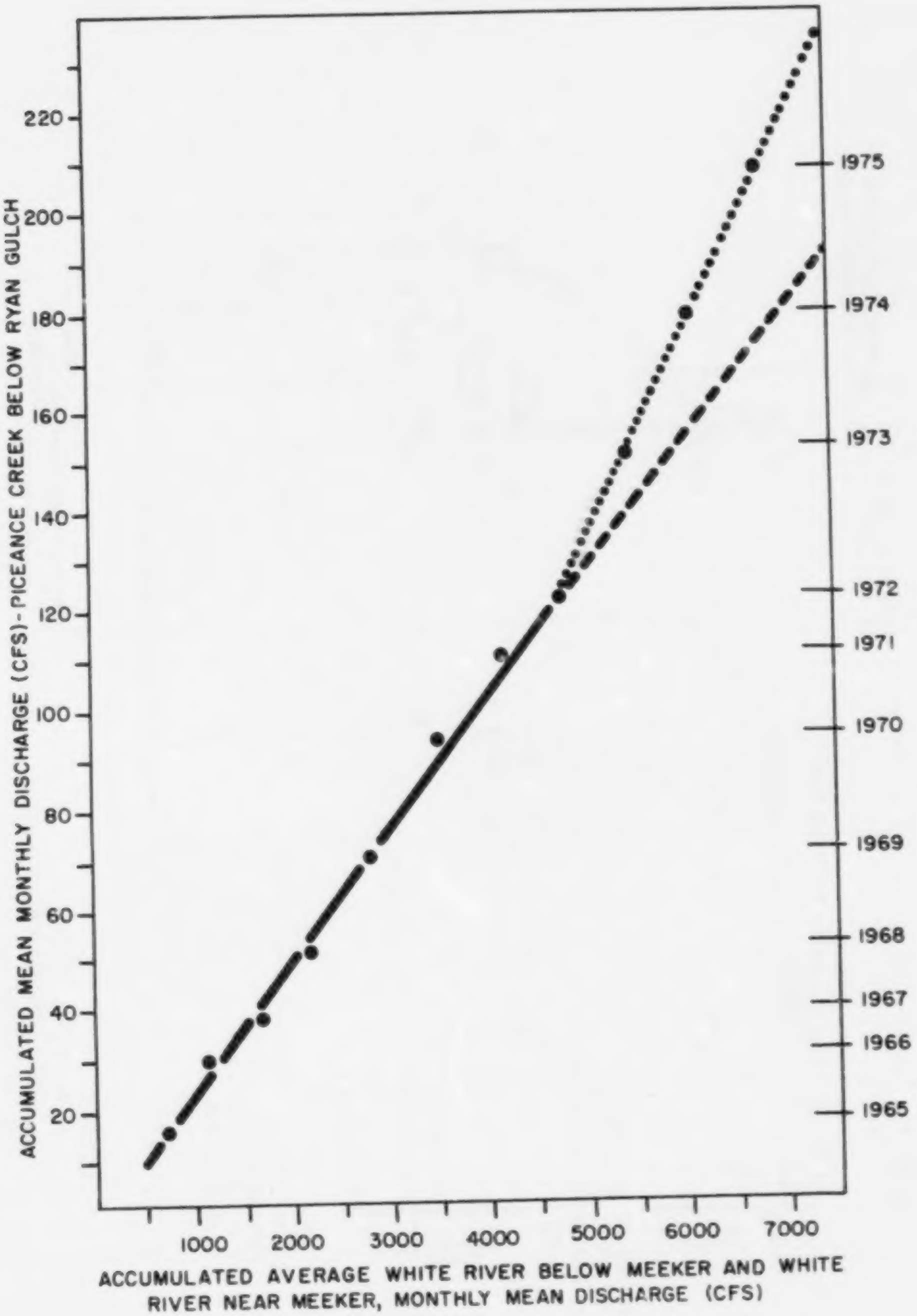


Figure 5-23. Double-mass curve for White River near Meeker and below Meeker and Piceance Creek below Ryan Gulch (C-b Shale Oil Venture, 1977b).

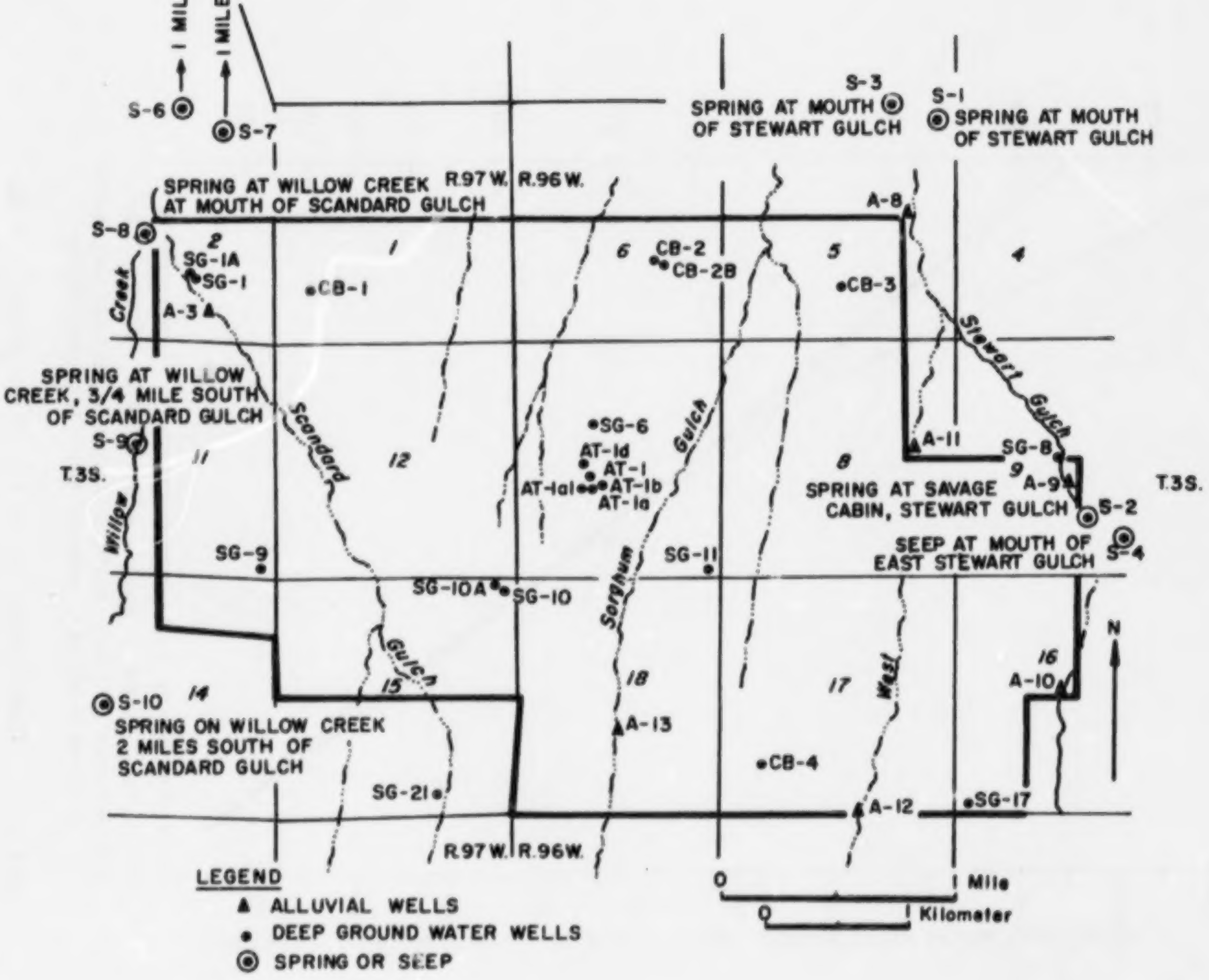

S-6
1 MILE
S-7
1 MILE
S-3
SPRING AT MOUTH OF STEWART GULCH
S-1
SPRING AT MOUTH OF STEWART GULCH
SPRING AT WILLOW CREEK AT MOUTH OF SCANDARD GULCH
R.97 W.
R.96 W.
S-8
A-8
2
SG-1A
SG-1
CB-1
1
6
CB-2
CB-2B
5
CB-3
4
A-3
Creek
SPRING AT WILLOW CREEK, 3/4 MILE SOUTH OF SCANDARD GULCH
S-9
Scandard
SG-6
Gulch
Stewart Gulch
T.3S.
11
12
AT-1d
AT-1
AT-1al
AT-1b
AT-1a
8
A-11
SG-8
9
A-9
T.3S.
SPRING AT SAVAGE CABIN, STEWART GULCH
S-2
Willow
SG-9
SG-11
SEEP AT MOUTH OF EAST STEWART GULCH
S-4
SG-10A
SG-10
Sorghum
N
Gulch
18
17
West
16
A-10
S-10
14
15
SPRING ON WILLOW CREEK 2 MILES SOUTH OF SCANDARD GULCH
A-13
CB-4
SG-21
A-12
SG-17
R.97 W.
R.96 W.
0
1 Mile
0
1 Kilometer
LEGEND
▲ ALLUVIAL WELLS
• DEEP GROUND WATER WELLS
◉ SPRING OR SEEP

Figure 5-24. Springs and seeps in the Tract C-b area (C-b Shale Oil Venture, 1977b).

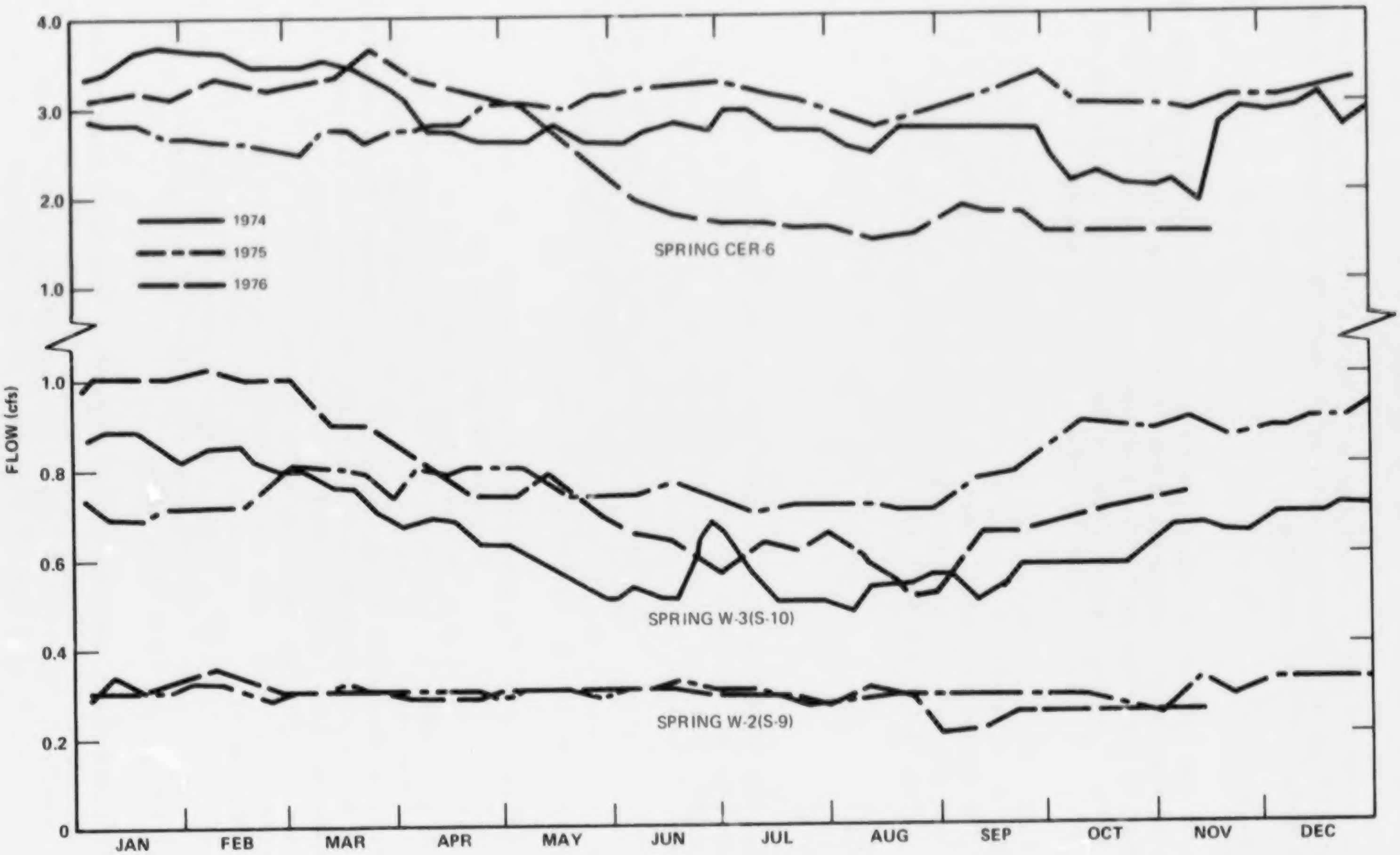


Figure 5-25. Hydrographs of springs near Tract C-a, 1974-1976 (C-b Shale Oil Venture, 1977b).

varies seasonally, declining in the spring when the alluvium is recharged and rising in the autumn. Daily flow measurements were taken on spring S-9 in an attempt to correlate spring discharge with barometric pressure fluctuations, but no correlation was observed, indicating that the spring source probably was not a deep, confined aquifer.

Alluvial Aquifers

Some of the springs are supplied by groundwater from the alluvium which lines the valley floors. Observed water levels in the alluvium peak in July and diminish to a minimum by February or March. This cycle is out of phase with the snowmelt supply, which peaks in March and April and is low in the summer. The lag is probably due to infiltration and seepage time.

The saturated thickness of the alluvium around Tract C-b ranges from 10 to 72 feet. The transmissivity varies radically, from 121 to 10,000 ft^2 per day. The variation probably depends on the nature of the alluvium penetrated and is not correlated with drainages or well depth. Specific yields averaging about 15 percent were also calculated from aquifer tests.

Deep Aquifers

Upper Aquifer--

The entire Tract C-b area is underlain by the Upper Aquifer. Figure 5-21 illustrates the configuration of this aquifer. It is bounded on the bottom by the Mahogany Zone confining bed and extends upward into the Uinta Formation. The Four Senators oil shale sequence, located at about the middle of the aquifer, serves as an aquitard, partially dividing the aquifer. Principal aquifer zones occur about midway between the Mahogany and Four Senators Zones and at the Green River Tongues in the Uinta Formation. The Black Sulfur Tongue seems to bound the aquifer on the top.

A tentative map of the potentiometric surface of the Upper Aquifer is provided in Figure 5-26. The gradient is toward the north at about 100 feet per mile. The curvature and increased separation of the potentiometric lines to the east are caused by discharge of the aquifer to Piceance Creek. Near the center of the tract, well SG-6-3 has a head 9 feet higher than that of well AT-1C-3, which should be upgradient of it. However, the piezometers in these wells are not perforated over the same intervals, and the small section near the Mahogany Zone, which SG-6-3 is perforated opposite, may have a higher head than the thicker interval with which AT-1C-3 is in contact. If the indicated averages of head truly are representative, they indicate a recharge area near these wells. The source of any such recharge is not apparent, since the wells are on the top of a ridge and nearby canyons are small, with ephemeral water courses. For these reasons, the 6500-foot equipotential line does not reflect the values from these wells.

Aquifer parameters were determined through a long-term aquifer test. The well AT-1 was pumped for 24 days at a rate varying from 480 to 365 gallons per minute, allowed to recover for 5 days, then pumped for 5 days at about the same rate. Several shortcomings of this test necessitated reevaluation of the

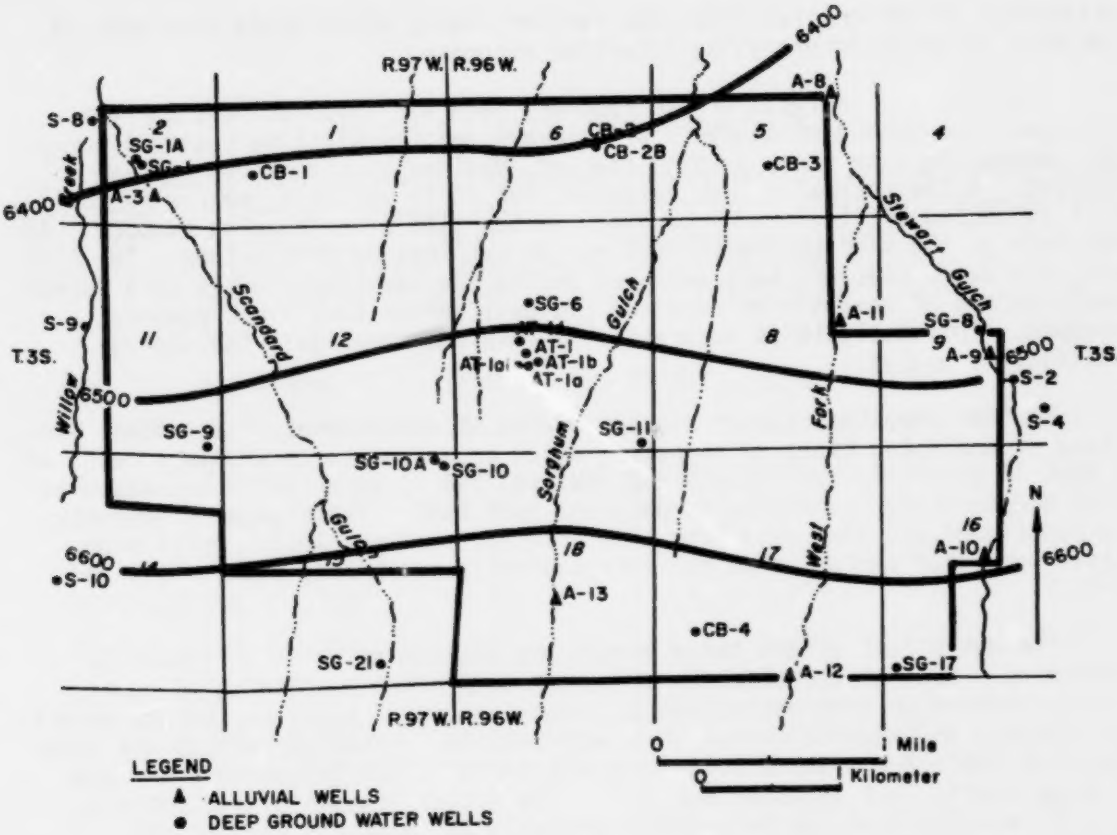

6400
R.97W.
R.96W.
S-8
2
SG-1A
SG-1
1
CB-1
6
CB-2
CB-2B
5
CB-3
A-8
4
Willow Creek
6400
A-3
Scandard
Stewart Gulch
S-9
T.3S.
11
12
SG-6
AT-1
AT-1b
AT-1a
Gulch
8
A-11
SG-8
9
A-9
6500
T.3S.
S-2
S-4
6500
SG-9
SG-11
Fork
SG-10A
SG-10
Sorghum
Gulch
N
6600
S-10
14
13
18
17
West
16
A-10
6600
A-13
CB-4
SG-21
A-12
SG-17
P.97W.
R.96W.
0
1 Mile
0
1 Kilometer
LEGEND
▲ ALLUVIAL WELLS
● DEEP GROUND WATER WELLS

Figure 5-26. Potentiometric surface of Upper Aquifer, Tract C-b. (C-b Shale Oil Venture, 1977b).

test and the data analysis by GE--TEMPO. A primary problem is the variation in discharge during what was supposed to be a constant discharge test. This variation amounted to about 24 percent of the initial rate. This decrease in pumping was nowhere accounted for in the subsequent analyses. A second problem is the uncertainty of response to longer pumping. The drawdown curves typically showed a normal curve, then a flattening at a later time. Such a response is characteristic of fractured rock aquifers, but is usually followed by another steepening of the curve, a result of the low permeability of the interfracture medium. The aquifer test was not carried out for long enough to determine if this late response would, in fact, occur. The transmissivity values which were published in the Tract C-b baseline report were taken from the early-time, steep curves, which gave low T figures. If the aquifer does respond to long-term pumping with a classic fracture response, these figures may be approximately correct, but the aquifer test simply was not long enough to determine what the response may be. A correction for residual drawdown should be made.

This problem was compounded by allowing only a 5-day measured recovery after the 23-day aquifer test. This period was not long enough to allow collection of the crucial late-time recovery data, which could have been of the most value in interpreting late-time response.

Finally, the analysis of the recovery data was invalid. The correct straight-line method of analysis of recovery data is plotting residual recovery versus log time since pumping started, divided by time since pumping stopped. A theoretically less reliable, but still valuable, method is to plot estimated ("calculated") recovery versus time since pumping stopped. An estimate of the storage coefficient may be obtained by this method. The AT-1 recovery data, however, were analyzed during the baseline studies by a normal Jacob method of analysis of drawdown (in psi) versus time since pumping stopped. This analysis is theoretically invalid, especially for storage coefficient analysis.

Another important factor was the method of measurement of drawdown. Instead of employing tapes or sounders, which are accurate to within a tenth of a foot if carefully used (Davis and DeWiest, 1966), water depth was measured with pressure gages accurate to only one-half foot. These gages frequently malfunctioned and thus data from many observations were lost. Drill stem tests were also performed to estimate aquifer permeability (Tables 5-5 and 5-6).

The net effect of all these errors and uncertainties is difficult to determine. Some of the effects counteract each other by tending to cause overestimation or underestimation of transmissivity. However, the net effect is probably an underestimation of transmissivity. Reported results are tabulated in Table 5-7. The average transmissivity is 168 ft^2 per day and the storage coefficient is about 5×10^{-4}. The actual transmissivity, according to reanalysis of the data, would probably be about 225 ft^2 per day. Reevaluation indicates a storage coefficient of 3×10^{-4}, but this difference is not significant. The higher transmissivity value is supported by USGS pumping tests. The average of six aquifer tests in the vicinity of Tract C-b reported in Weeks et al. (1974) is 405 ft^2 per day.

Leakance values, estimated from type-curve matching (Table 5-7), were small, showing that the water level in any aquifer was not affected by pumping any other aquifer. A computer solution of the Neuman and Witherspoon leaky aquifer equation was developed which indicated that the vertical hydraulic conductivity was less than 5×10^{-7}.

Fractured rock aquifers are typically anisotropic with greatest permeability in the direction of major fracturing. An evaluation of data from wells SG-6, SG-10, and SG-11 during the AT-1 aquifer test using R.E. Glover's equations for anisotropic analysis yielded a 9:1 ratio of maximum to minimum permeability, with the maximum in an east-northeast direction (C-b Shale Oil Venture, 1977b). Reevaluation by TEMPO of the AT-1B, AT-1C, and AT-1D data from the same aquifer test by GE--TEMPO using Hantush's method (Kruseman and DeRidder, 1976) yielded a 2:1 ratio with the maximum permeability N48W. The maximum transmissivity (assuming an effective transmissivity of 225 ft^2 per day, as discussed above) is 318 ft^2 per day and the minimum is 159 ft^2 per day. The 2:1 anisotropy seems more reasonable than 9:1. The N48W orientation is much more likely, as the regional joint strike is northwest. Nearby

TABLE 5-5. SG-17 DRILL STEM TESTS

Drill stem test no.	Interval (feet)	Permeability (md)	Drill stem test no.	Interval (feet)	Permeability (md)
1	386 - 436	N.D.[a]	23	1,512 - 1,572	4.0
2	788 - 808	N.D.	24	1,561 - 1,572	23.0
3	822 - 869	11.0	24(J)[b]	1,561 - 1,622	N.D.
4	866 - 919	12.7	25	1,618 - 1,640	4.0
5	919 - 970	34.0	25(J)	1,618 - 1,670	1.6
6	967 - 1,017	10.7	26	1,668 - 1,679	30.0
7	1,017 - 1,067	19.9	26(J)	1,668 - 1,720	7.3
8	1,066 - 1,116	20.0	27	1,711 - 1,770	6.0
9	1,116 - 1,166	8.0	28	1,768 - 1,779	42.0
10	1,164 - 1,212	185.0	28(J)	1,768 - 1,820	9.8
11	1,200 - 1,224	21.2	29	1,818 - 1,870	2.0
12	1,215 - 1,224	20.8	30	1,869 - 1,880	275
13	1,224 - 1,251	300	30(J)	1,869 - 1,910	30
14	1,251 - 1,271	8.0	31	1,918 - 1,970	4.0
15	1,280 - 1,309	13.0	32	1,966 - 2,020	169
16	1,309 - 1,336	N.D.	33	2,018 - 2,070	N.D.
17	1,327 - 1,373	52	34	2,120 - 2,170	30
18	1,373 - 1,419	15	35	2,220 - 2,270	N.D.
19	1,423 - 1,470	N.D.	36A	2,320 - 2,370	N.D.
20	1,423 - 1,470	23.9	36B	2,315 - 2,370	N.D.
21	1,473 - 1,522	3.0	37	2,395 - 2,460	35.0
22	1,428 - 1,522	4.7			

[a] N.D. = No data obtained due to equipment malfunction, analytical problems, no water injection, packer leakage, etc.

[b] (J) = Jetting test.

TABLE 5-6. SG-17 MULTIPACKER TESTS

Multipacker test no.	Interval (feet)	Permeability (md)
1	1,089 - 1,114	75
2	1,123 - 1,148	N.D.[a]
3	1,147 - 1,172	92
4	1,184 - 1,209	N.D.
5	1,338 - 1,363	N.D.
6	1,422 - 1,477	N.D.

[a] N.D. = No data obtained due to equipment malfunction, analytical problems, no water injection, packer leakage, etc.

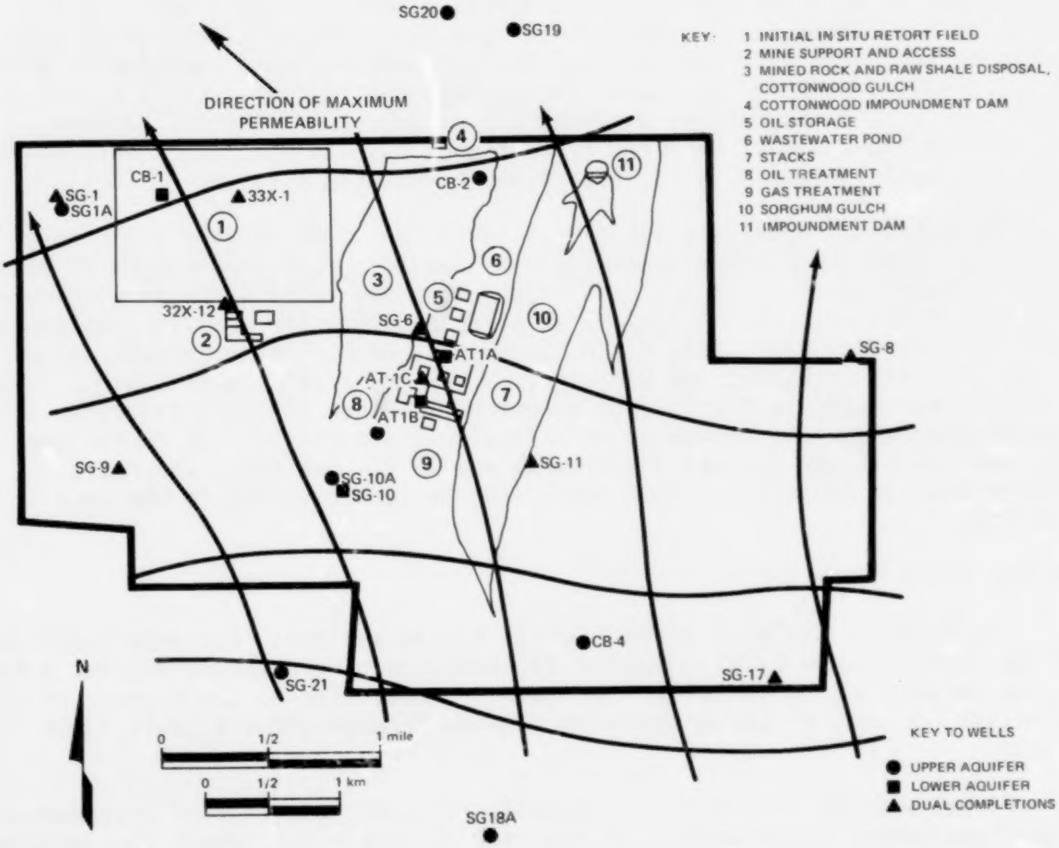
TABLE 5-7. RESULTS OF AQUIFER TESTS ON OIL SHALE LEASE TRACT C-b (C-b Shale Oil Venture, 1977b).

Well no. (string no.)	Transmissivity (ft^2 per day)	Storage coefficient	Leakage (day^{-1})
Upper Aquifer			
SG-10	233	4.21×10^{-4}	4.26×10^{-7}
AT-1A (3)	159	4.23×10^{-4}	6.10×10^{-6}
SG-6	212	1.68×10^{-3}	1.27×10^{-6}
AT-1D (3)	130	2.97×10^{-4}	8.05×10^{-7}
AT-1B	162	3.71×10^{-4}	1.56×10^{-6}
AT-1C	128	2.73×10^{-4}	1.23×10^{-6}
SG-11	155	6.92×10^{-5}	5.90×10^{-7}
Lower Aquifer			
AT-1C (2)	20.4	1.22×10^{-4}	1.96×10^{-5}
AT-1C (1)	40.9	1.21×10^{-5}	3.93×10^{-7}
AT-1D (1)	35.4	2.67×10^{-5}	8.77×10^{-7}
SC-6 (1)	91.9	5.30×10^{-4}	---
AT-1D (1)	43.8	4.19×10^{-4}	---
SG-6 (2)	35.7	6.84×10^{-5}	3.44×10^{-6}
SG-10 (10)	14.7	3.92×10^{-5}	6.88×10^{-6}

faults mapped in Weeks et al. (1974) strike N68W. Bredehoeft et al. (1976) reported that hydraulic fracturing experiments indicated a regional fracturing orientation of N70W. The Tract C-a Detailed Development Plan (RBOSP, 1976) reported that the major joint set strikes N56-76W. The east-northeast orientation calculated for Tract C-b is nearly perpendicular to the regional trend, while N48W is quite close to it. The flow net in Figure 5-27 is drawn using these anisotropy values and orientations by the anisotropic flow net transform method. The anisotropy causes the flow lines to diverge by more than a mile across the tract.

Lower Aquifer--

The Lower Aquifer under Tract C-b extends from the lower half of the Mahogany Zone to the R (rich oil shale) -4 zone (Figure 5-21). Major water-producing zones are the lower part of the Mahogany Zone, and the lower half of the R-5 with the L-4 below it. The upper half of the R-5 zone forms an intermediate aquitard and the lower R-4 zone the base of the aquifer. The



SG20
SG19
DIRECTION OF MAXIMUM PERMEABILITY
KEY:
1 INITIAL IN SITU RETORT FIELD
2 MINE SUPPORT AND ACCESS
3 MINED ROCK AND RAW SHALE DISPOSAL, COTTONWOOD GULCH
4 COTTONWOOD IMPOUNDMENT DAM
5 OIL STORAGE
6 WASTEWATER POND
7 STACKS
8 OIL TREATMENT
9 GAS TREATMENT
10 SORGHUM GULCH
11 IMPOUNDMENT DAM
SG-1
SG1A
CB-1
33X-1
CB-2
32X-12
SG-6
AT1A
AT-1C
AT1B
SG-8
SG-9
SG-10A
SG-10
SG-11
CB-4
SG-17
SG-21
N
0
1/2
1 mile
0
1/2
1 km
SG18A
KEY TO WELLS
● UPPER AQUIFER
■ LOWER AQUIFER
▲ DUAL COMPLETIONS

Figure 5-27. Anisotropic flow net of Upper Aquifer superimposed on Tract C-b initial development plot plan.

R-4 is just above the saline (high resistivity) zone at the base of the Parachute Creek Member. A few thin strata, containing water with high dissolved solids from direct contact with the saline zone, lie below the R-4.

The head of the Lower Aquifer is everywhere (on Tract C-b) below that of the Upper Aquifer. The potentiometric surface of the Lower Aquifer is mapped in Figure 5-28. The curvature of the lines to the east indicates possible discharge to Piceance Creek. No anomaly similar to that in the Upper Aquifer was found.

The design of the aquifer test performed in the Lower Aquifer was similar to the Upper Aquifer test. The well was pumped for 18 days at 130 gallons per minute, allowed to recover for 8 days, pumped for 8 more days, and allowed to recover for 20 days. Factors affecting the results of this test are similar to those discussed above, except that here the pumping rate was fairly constant. However, another influence in this test was the fact that the well depth was only 1700 feet, penetrating only a little more than half the aquifer. Partial penetration will cause the transmissivity to be underestimated. The Tract C-b baseline report transmissivity values are listed in Table 5-7. The average is 40.4 ft^2 per day. Reanalysis indicates that a more representative transmissivity is about 70 ft^2 per day. The high T value is supported by the average of nearby Lower Aquifer pumping tests reported in Weeks et al. (1974) of 100 ft^2 per day. The average coefficient is 1.73×10^{-4} (10^{-4} to 5×10^{-5} is probably a reasonable range) (C-b Shale Oil Venture, 1977b). On the basis of barometric efficiency calculations, the baseline report concluded the porosity is about 0.05, a reasonable value.

The baseline report did not give figures for Lower Aquifer anisotropy, but stated that the maximum transmissivity was in a more north-south direction than the Upper Aquifer. Reanalysis showed that the results varied considerably when different combinations of wells were used. The results considered most reliable were from wells AT-1A, SG-10, and SG-6. Using Hantush anisotropic analysis (Kruseman and DeRidder, 1976), the direction of maximum transmissivity was N81W, in fairly good agreement with the geologic evidence. The maximum transmissivity (assuming an effective transmissivity of 70 ft^2 per day) was 146 ft^2 per day and the minimum was 33 ft^2 per day. The ratio between them is about 4:1. This conclusion is tentative due to the data problems.

SURFACE WATER HYDROLOGY

The Piceance Basin is drained by two stream systems: Piceance Creek and Yellow Creek (Figure 5-29). Most of the tributaries are ephemeral, but a few of the largest are perennial in the lower reaches. Two or three years of data now exist for most of the tributaries flowing through the oil shale lease tracts.

Piceance Creek maintains a reasonably constant base flow of groundwater. Peak flows occur in the spring, at the time of snowmelt. Summer thunderstorms can also raise the flow. The maximum, minimum, and mean monthly flows are shown in Figure 5-30. The discharge at Rio Blanco is nearly unaffected by

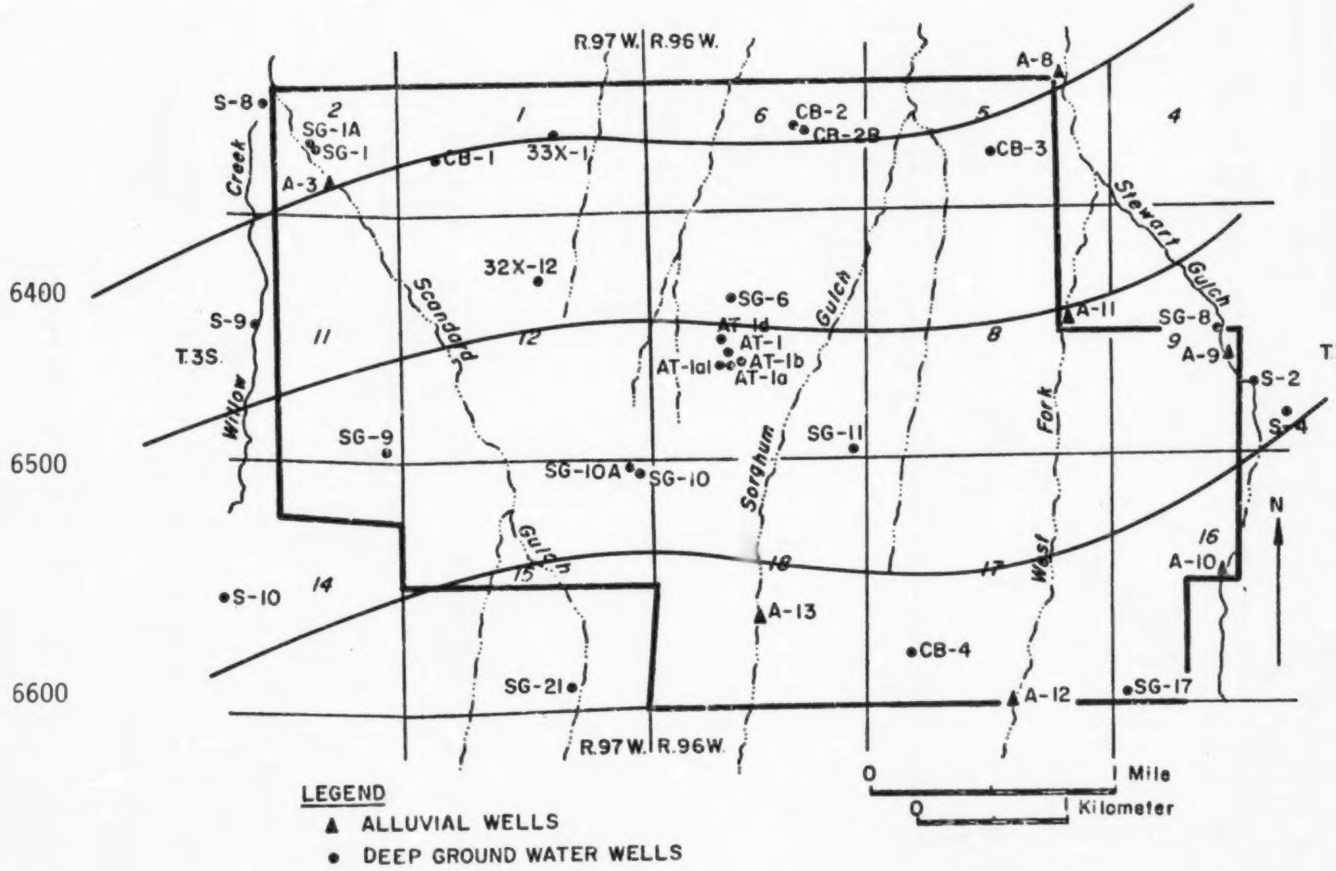
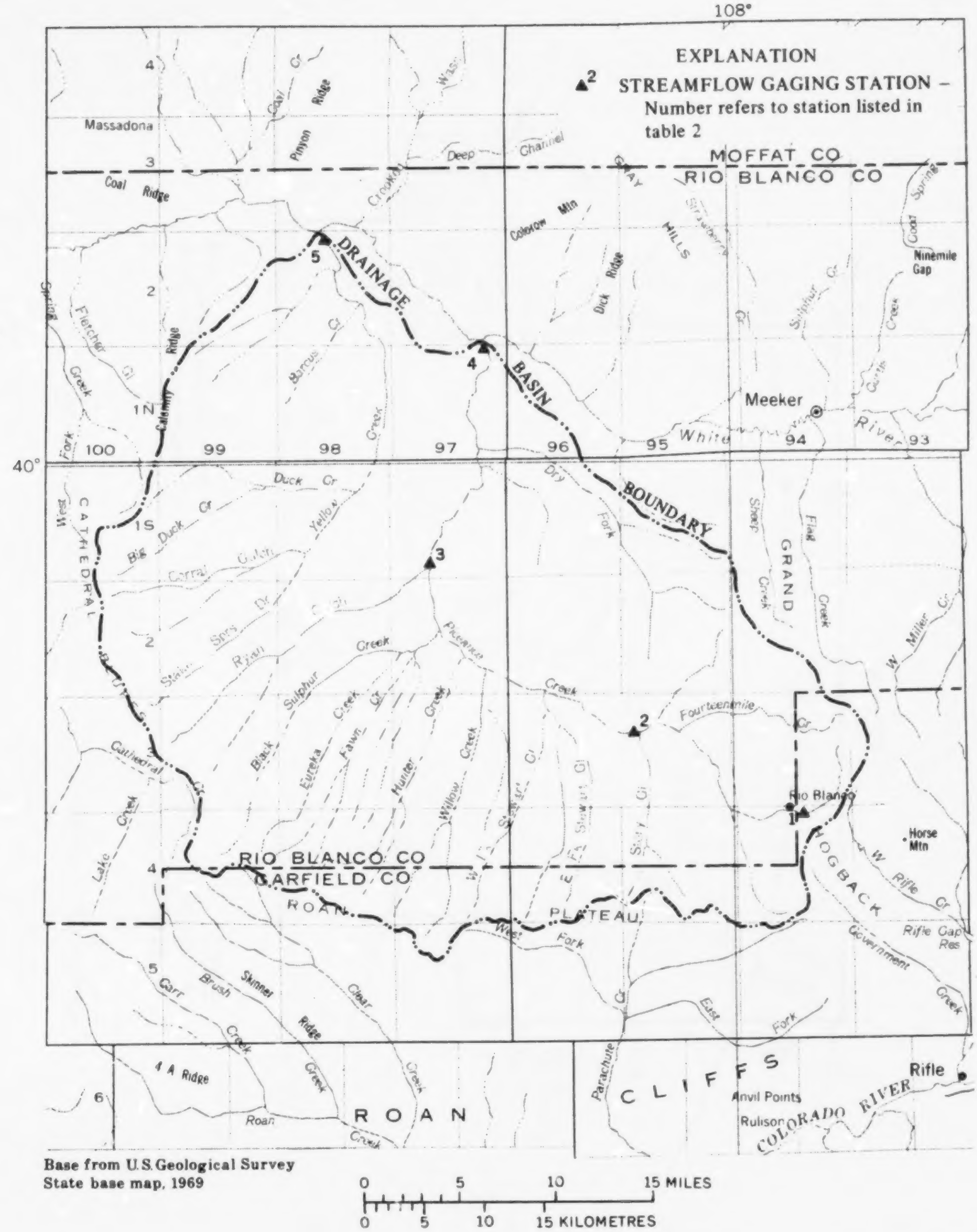

R.97 W.
R.96 W.
T.3S.
T.3S.
6400
6500
6600
S-8
S-9
S-10
SG-1A
SG-1
A-3
CB-1
33X-1
32X-12
SG-9
SG-10A
SG-10
SG-21
CB-2
CB-2B
SG-6
AT-1d
AT-1
AT-1b
AT-1a
AT-1a1
SG-11
A-13
CB-3
CB-4
A-8
A-11
A-12
SG-8
A-9
S-2
S-4
A-10
SG-17
2
1
6
5
4
11
12
8
9
14
15
18
17
16
Willow Creek
Scandard Gulch
Sorghum Gulch
West Fork
Stewart Gulch
N
0
1 Mile
0
1 Kilometer
LEGEND
▲ ALLUVIAL WELLS
● DEEP GROUND WATER WELLS

Figure 5-28. Lower Aquifer potentiometric map, Tract C-b.


108°
40°
EXPLANATION
▲2 STREAMFLOW GAGING STATION – Number refers to station listed in table 2
MOFFAT CO
RIO BLANCO CO
GARFIELD CO
DRAINAGE BASIN BOUNDARY
Massadona
Meeker
Rio Blanco
Rifle
Anvil Points
Rulison
Ninemile Gap
Horse Mtn
Rifle Gap Res
White River
COLORADO RIVER
ROAN PLATEAU
ROAN CLIFFS
CATHEDRAL BLUFFS
GRAND HOGBACK
GRAY HILLS
Piceance Creek
Yellow Creek
Fourteenmile Cr
Parachute Cr
1
2
3
4
5
100
99
98
97
96
95
94
93
1N
1S
0 5 10 15 MILES
0 5 10 15 KILOMETRES

Base from U.S. Geological Survey
State base map, 1969

Figure 5-29. Location of streamflow gaging stations (Weeks et al., 1974).

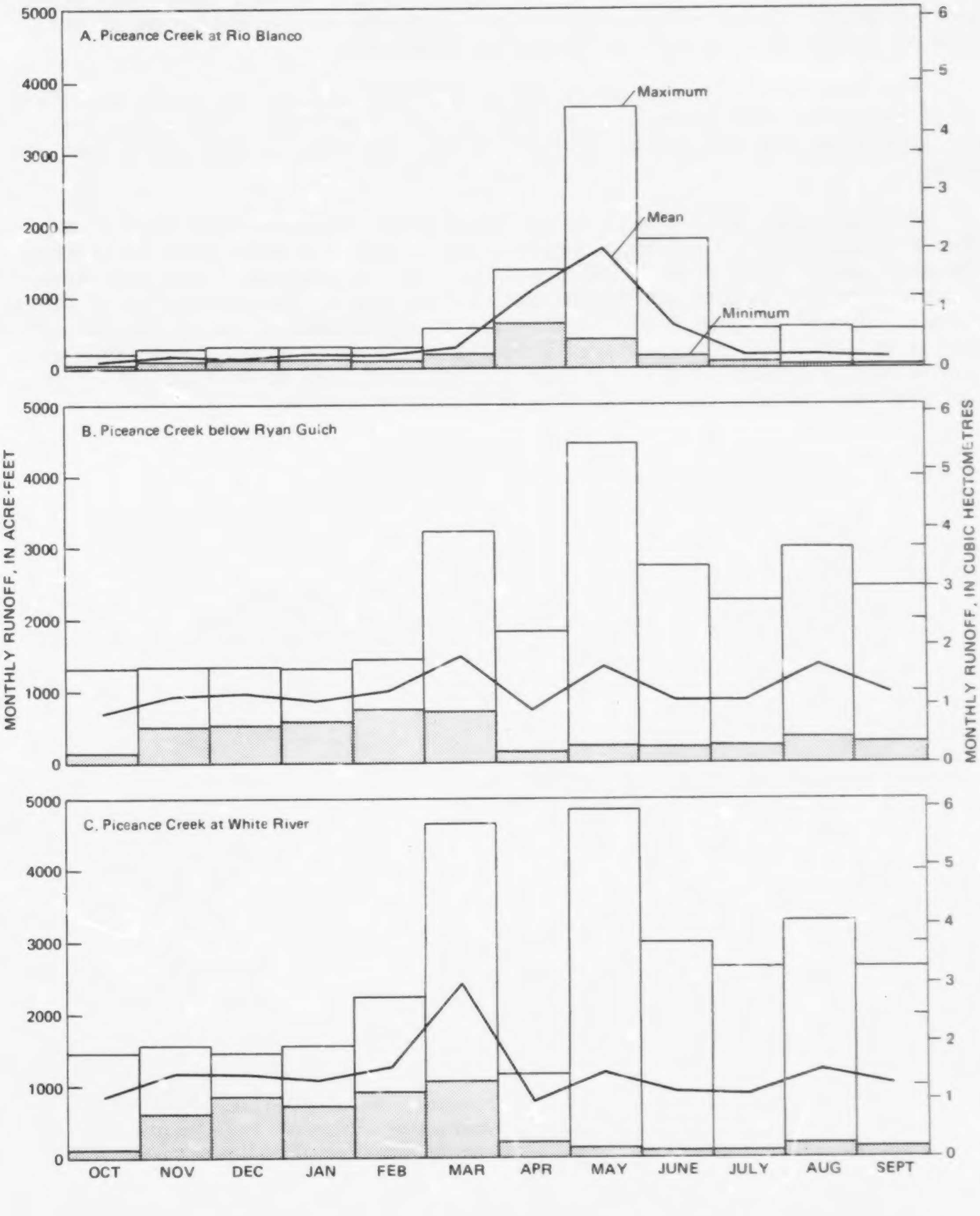


Figure 5-30. Maximum, minimum, and mean monthly runoff from Piceance Creek at Rio Blanco, below Ryan Gulch, and at White River.

human activity, but the flows at the two lower stations are altered by diversion for irrigation of hay fields and pastureland. Approximately 5100 acres are irrigated. Large withdrawals in April and May at the beginning of the growing season greatly modify the spring flood peak.

The mean annual discharge at the White River amounts to 14,520 acre-feet (17.6 cubic feet per second). The mean annual high flow is 800 cubic feet per second and the calculated 20-year, 7-day, low flow is 10.4 cubic feet per second.

Yellow Creek, with a smaller drainage basin, contains much less flow than Piceance Creek. The mean annual flow is only 1.4 cubic feet per second. The mean annual high flow is 388 cubic feet per second, but flows less than 1 cubic foot per second are common and, in dry years, the stream may at times be dry. Runoff (Figure 5-30) is affected by withdrawal of water for the irrigation of about 200 acres. Because of the small basin size, summer thunderstorms have a proportionately greater effect than they do on Piceance Creek. For the same reason, the variability of flows is greater.

SECTION 6

EXISTING WATER QUALITY

The hydrologic system of the Piceance Basin may be divided into four general parts: surface water, alluvial aquifers, the Upper Aquifer, and the Lower Aquifer. The lithology of the rocks over or through which the water flows largely determines the water quality. Some broad generalizations on the regional water quality may be made.

GENERAL BASIN WATER QUALITY

Surface water quality within the Piceance Basin is widely variable. The streams pick up salts from runoff over saline soils as they flow downstream. Salts already present are concentrated by evapotranspiration. The major contributor of salts is probably influent water ultimately derived from the saline groundwaters, particularly from the Lower Aquifer.

The total dissolved solids content of the surface waters increases from around 600 mg/l near the headwaters of Piceance Creek to 2000 mg/l at the White River. The water is a mixed-cation bicarbonate to a sodium bicarbonate type.

The water of the Lower Aquifer displays a similar pattern of salinity. In this case it is due to dissolution of saline minerals as the groundwater flows toward the discharge area. Some beds at the base of the leached zone are nearly pure nahcolite and halite. The total dissolved solids content increases from about 500 mg/l to nearly 40,000 mg/l (Figure 6-1). The average is 9400 mg/l. Obviously, this salinity renders much of the water in the aquifer unsuitable for many uses.

The water is of fairly pure sodium bicarbonate type, with chloride as the only other major ion. Calcium and magnesium are very low, partly because the minerals dissolved are primarily sodium salts and partly because of concentration control by calcite solubility limits. Chloride is significant because of halite in the aquifer. Sulfate concentrations are relatively low, averaging about 80 mg/l. Certain trace elements are also extremely high. Even in regions of lower salinity, the fluoride content is over 10 mg/l and may reach over 60 mg/l. In the high salinity region, barium concentrations of 13 mg/l, boron concentrations of 120 mg/l, and lithium concentrations of 6 mg/l have been measured.

The Upper Aquifer is not characterized by these extreme salinity and trace element concentrations. Dissolved solids do increase from 350 mg/l

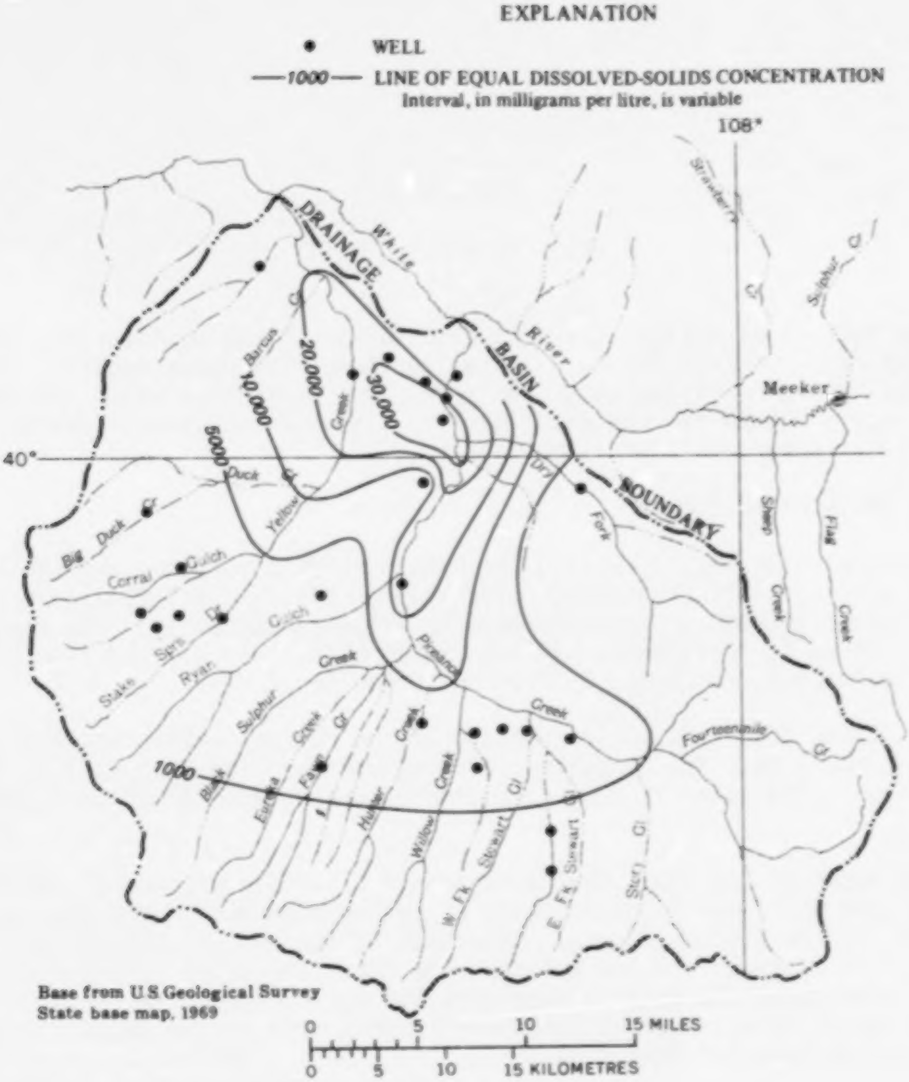

EXPLANATION
WELL
1000 LINE OF EQUAL DISSOLVED-SOLIDS CONCENTRATION
Interval, in milligrams per litre, is variable
108°
40°
DRAINAGE
BASIN
BOUNDARY
White River
Meeker
Strawberry Cr
Sulphur Cr
Barcos Cr
Creek
Duck Cr
Big Duck Cr
Corral Gulch
Yellow
Stake Sprs Dr
Ryan Gulch
Sulphur Creek
Black
Eureka Creek
Fawn Cr
Hunter
Willow Creek
W. Fk. Stewart Cr
E. Fk. Stewart Cr
Stewart Gl
Dry Fork
Piceance Creek
Fourteenmile Cr
Sheep Creek
Flag Creek
Scandard Gl
1000
5000
10,000
20,000
30,000
Base from U.S. Geological Survey
State base map, 1969
0 5 10 15 MILES
0 5 10 15 KILOMETRES

Figure 6-1. Concentration of dissolved solids in the Lower Aquifer, May-September 1973 (Weeks et al., 1974).

near the recharge areas to over 2000 mg/l in the basin center (Figure 6-2), but this increase is not accompanied by high trace elements. The water is of a similar type to that of the Lower Aquifer, with a sodium bicarbonate character and moderate chloride. However, fluoride is very low, and so are other trace elements.

The type of the alluvial aquifer water is quite similar to that of the Upper Aquifer. The dissolved solids range from 500 to 6700 mg/l. It is of a sodium bicarbonate type with a higher sulfate concentration than the other

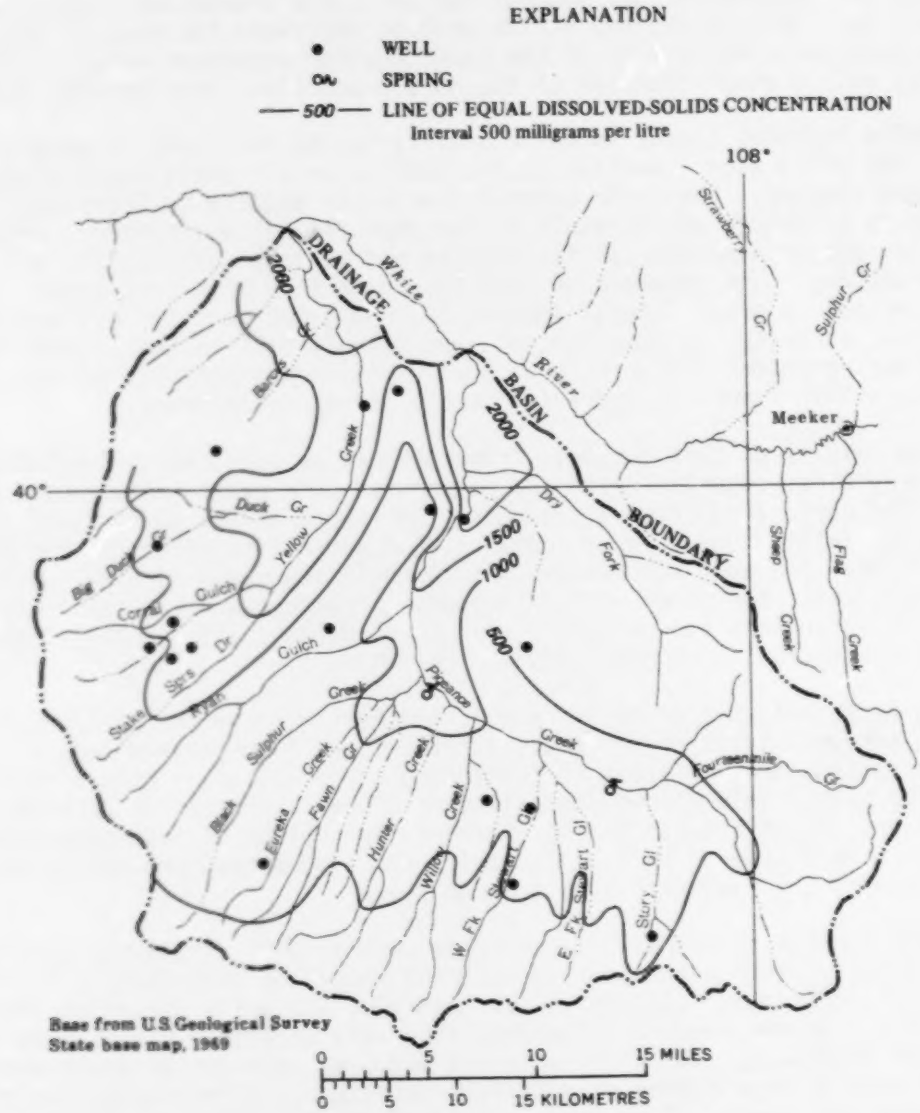

EXPLANATION
● WELL
SPRING
—500— LINE OF EQUAL DISSOLVED-SOLIDS CONCENTRATION
Interval 500 milligrams per litre
108°
40°
DRAINAGE
BASIN
BOUNDARY
2000
1500
1000
500
White River
Meeker
Strawberry Cr
Sulphur Cr
Sheep Creek
Flag Creek
Barcus Cr
Duck Cr
Big Duck Cr
Corral Gulch
Yellow Creek
Dry Fork
Stake Sprs Dr
Ryan Gulch
Piceance Creek
Fourteenmile Cr
Black Sulphur Creek
Eureka Creek
Fawn Cr
Hunter Creek
Willow Creek
W. Fk Stewart Gl
E. Fk Stewart Gl
Stury Gl
Base from U.S. Geological Survey
State base map, 1969
0 5 10 15 MILES
0 5 10 15 KILOMETRES

Figure 6-2. Concentration of dissolved solids in the Upper Aquifer, May-September 1973 (Weeks et al., 1974).

groundwaters of the area, averaging 430 mg/l. In general, fluoride content is low. The average dissolved solids content is 1750 mg/l, much lower than the maximum of 6700 mg/l. The areas with high dissolved solids content are near faults which allow discharge of high salinity water from the deep aquifers to the alluvial aquifer (Weeks et al., 1974).

The nature of the groundwater in the Piceance Basin may cause several problems for groundwater development for oil shale production. Water of under 1000 mg/l total dissolved solids will be desirable for many of the processes involved. While much of the Upper Aquifer possesses water of this quality, only a small fraction of the more productive Lower Aquifer does.

While regional trends in water quality may be described in general terms, the pattern on a smaller scale, such as an oil shale lease tract, is much more complex. The major control over water quality is lithology. Changes in lithology are a result of the depositional environment, which was a complex system dependent on fluctuating sedimentary, biological, and chemical parameters. The sequence of rock resulting from this environment is characterized by great lateral continuity, and great vertical differences in rock type, strength, kerogen content, and soluble salt content. Each of these layers has responded differently to post-depositional tectonic stresses, and response within layers to hydraulic stress is not homogeneous.

The results of this geologic framework may be pictured by imagining two wells very close together which are perforated over exactly the same intervals. The perforated interval contains two fractured strata of equal hydraulic conductivity. One stratum contains abundant saline minerals, the other very little. One well intersects a fracture in the upper stratum but not in the lower, while the other well intersects a fracture only in the lower stratum. The water from the two wells will be of drastically different quality even if the hydraulic conductivity is the same.

In fact, this situation is complicated even more by the differing hydraulic conductivities of different strata. Some fine-grained beds with high kerogen content are resistant to fracturing or jointing and form effective confining beds. This allows the existence of head differences between saturated layers, which creates mixing of waters in regions of interconnection, such as in well bores. On a small scale, the system may more nearly resemble 10 to 20 very thin aquifers than 2 large ones.

This complexity necessitates extreme care in analyzing water quality data. Ideally, each water-bearing interval should be individually isolated at several locations. If this is not possible, all wells should at least be perforated over the same stratigraphic intervals or over a small number of different intervals. On both Tracts C-a and C-b, observation wells are perforated over a large number of different stratigraphic intervals, few of which correspond the others. Thus, the individual tract results should be viewed with great caution until more complete data are obtained.

TRACT C-a GROUNDWATER QUALITY

General Description

About 32 wells were drilled and monitored during the Tract C-a baseline monitoring period. Most of these wells were perforated in, or open to, both aquifers. Most holes were 6-3/4 inches in diameter, with the main aquifer zones separated by means of a mechanical packer. Monitored intervals in the Upper Aquifer were usually accessed by the insertion of perforated 2-3/8-inch tubing. The lower portion of the hole, below the packer, was usually left open, with 2-3/8-inch tubing leading from the packer to the surface.

Data on alluvial water quality are summarized in Table 6-1. The temporal variation of some of these parameters is shown in Figure 6-3. The decrease in most parameters around April is probably due to dilution of aquifer water by infiltrating snowmelt (RBOSP, 1977b).

The compositions of water samples from wells in the Upper and Lower Aquifers are plotted on a trilinear diagram in Figure 6-4. The variation in composition of samples from the same aquifers is much larger than that from Tract C-b (see following discussion). In general, the Upper Aquifer waters contain 35 to 70 percent sodium plus potassium, 10 to 40 percent calcium, and roughly equal magnesium. The anion composition is an approximately equal sulfate-bicarbonate type, with less than 10 percent chloride plus fluoride.

The Lower Aquifer exhibits a much wider range of composition. Sodium generally comprises a higher percentage of the cations (60 to 100 percent), while calcium is much lower (0 to 10 percent). Magnesium is 0 to 25 percent. The anions are dominated by carbonate plus bicarbonate (60 to 100 percent), with 0 to 35 percent sulfate and minor chloride plus fluoride. Many samples fall outside of these ranges, some in the trilinear diagram field of the other aquifers and some are completely different from all the rest. Several of the Lower Aquifer wells have water higher in magnesium and sulfate than any of the Upper Aquifer wells. While these anomalous samples are difficult to account for, the general explanation of the water quality distribution is probably that the Upper Aquifer water quality is influenced by leaching of the oxidized products from surface weathering, while the Lower Aquifer is chemically reduced and more heavily affected by the leaching of soluble salts within the aquifer.

The lateral distribution of the major cations and anions in the Upper and Lower Aquifers was mapped as part of this study. However, the distributions made sense neither in relation to the geochemical system nor in relation to each other. The likely explanation is that the wells are not consistently perforated with respect to the stratigraphy and water quality (which reflect the mineralogy and residence time within the individual strata). The situation on Tract C-a is further complicated by the complex structure and particularly the widespread faulting.

Water Type Comparisons

The compositions of the various well samples were compared with pH, TDS, and temperature in order to determine more exact relationships. Figure 6-5 shows a fair correlation of composition with pH in the Upper Aquifer. The pH of most Upper Aquifer samples is below 7.4. The Lower Aquifer exhibits a wide range of pH, from below 7.0 to about 8.0, but the correlation with composition is good. Most of the Lower Aquifer samples with high calcium, magnesium, and sulfate have pH values below 7.4, while those with high sodium and bicarbonate content have pH values above 7.5.

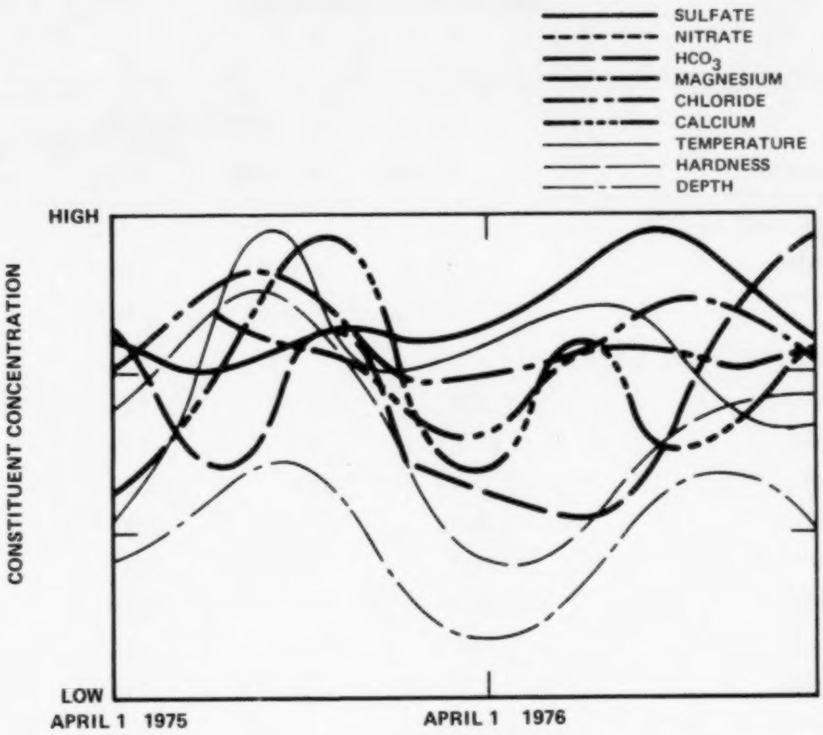
TABLE 6-1. SUMMARY OF WATER QUALITY FROM ALLUVIAL AQUIFERS, TRACT C-a (RBOSP, 1977b)

Constituent	Concentration Maximum	Minimum	Geometric mean	Number of analyses
General water quality measures				
Conductivity (μmhos/cm)	2,252	860	1,288	67
Dissolved solids (mg/l)	1,650	610	777	67
Alkalinity (mg/l $CaCO_3$)	880	310	383	67
pH	7.2	6.0	6.3	63
Hardness (mg/l Mg, Ca)	810	280	448	62
Temperature (^{o}F)	57.2	42.0	48.8	67
Fecal coliforms (per 100 ml)	40	< 10	20	2
Total coliforms (per 100 ml)	250	20	71	2
Major inorganics (mg/l)				
Bicarbonate	680	360	459	67
Carbonate	48	< 0.1	0.3	67
Chloride	41	1.3	12.8	65
Sulfate	720	150	297	67
Sulfide	1.6	< 0.1	0.2	11
Fluoride	0.7	0.1	0.3	66
Nitrate (NO_3)	165	0.1	3.9	61
Nitrite (N)	150	< 0.01	0.22	19
Ammonia (N)	5.3	< 0.1	0.4	14
Calcium	210	39	96	67
Magnesium	145	3.7	57	65
Sodium	350	60	151	67
Potassium	14	< 1	3.7	22
Phosphate (PO_4)	0.1	0.1	0.1	20
Organics (mg/l)				
Biochemical oxygen demand	3.9	3.8	3.9	2
Dissolved organic carbon	292	2	18.7	55
Phenolics (μg/l)	13	< 1	2	11
Kjeldahl nitrogen	8.8	< 0.1	1.8	22

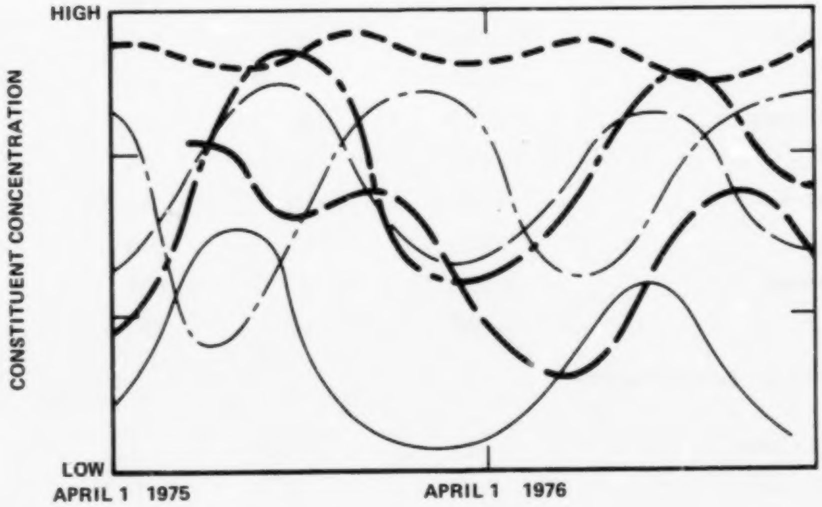
(continued)

TABLE 6-1. (continued)

	Concentration			
Constituent	Maximum	Minimum	Geometric mean	Number of analyses
Organics (mg/l) (con't.)				
Cyanide	0.02	< 0.01	0.01	55
MBAS	< 0.01	< 0.01	< 0.01	2
Trace constituents (μg/l)				
Aluminum	1,200	<100	142	11
Arsenic	<100	<10	<11	53
Barium	< 1,000	< 1,000	< 1,000	45
Beryllium	600	< 20	106	3
Boron	27,000	< 10	190	65
Bromide	900	< 10	150	8
Cadmium	1,100	< 10	17	54
Chromium	200	< 10	11	54
Copper	2,400	< 10	12	56
Iron	28,000	< 50	11	67
Lead	1,000	10	138	56
Manganese	15,000	< 50	575	64
Mercury	<10	< 1	< 3	56
Molybdenum	<100	<100	<100	6
Nickel	200	10	54	45
Selenium	<100	<10	<10	56
Silver	<100	<10	<13	45
Strontium	5,000	1,400	2,500	6
Zinc	3,200	10	290	56
Radiological constituents (pCi/l)				
Gross alpha	31	0.2	7.3	45
Radium 226	1	0.1	0.3	27
Gross beta	35	1.0	9.5	13



BOX ELDER GULCH
G-S S-7



CORRAL GULCH
G-S S-8

Figure 6-3. Time trend plots for concentrations of chemical constituents in Tract C-a alluvium (RBOSP, 1977b).

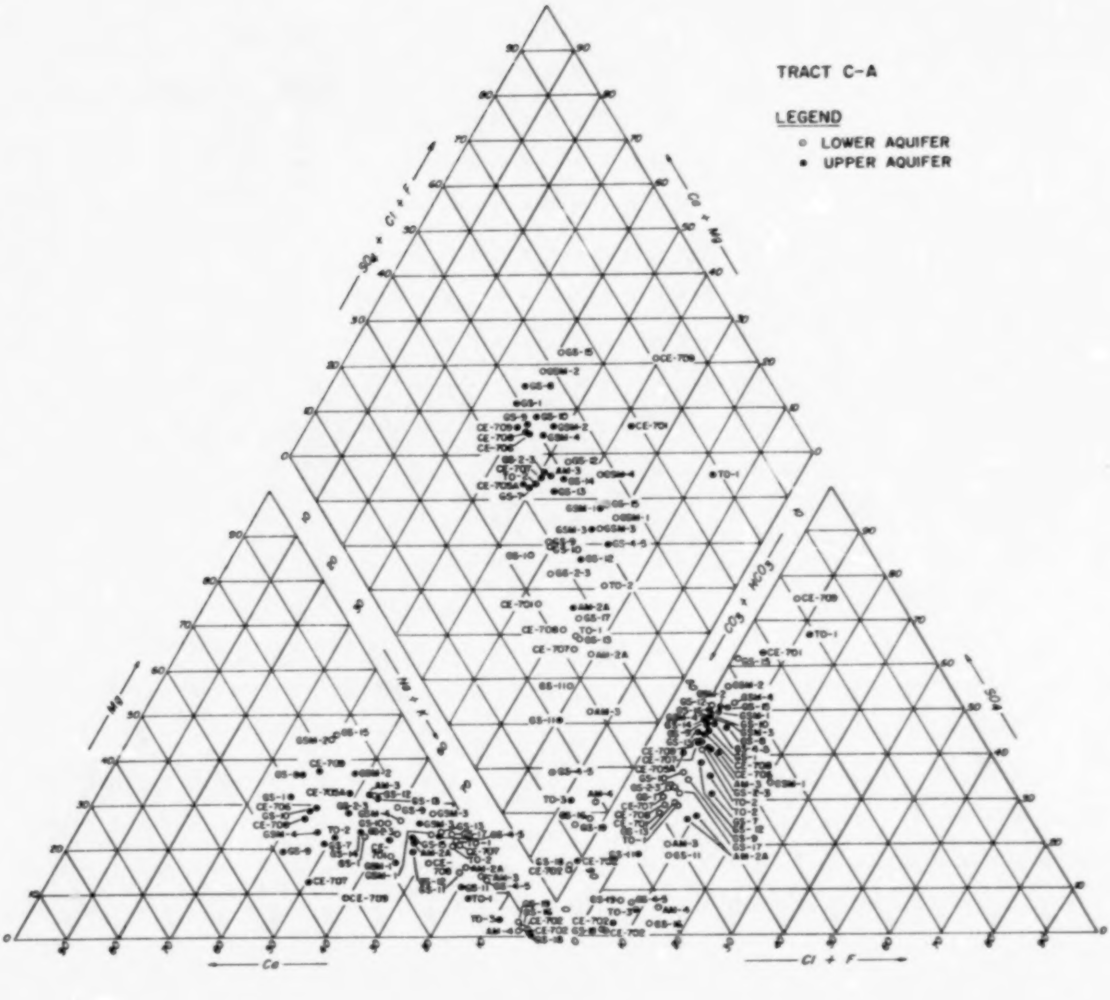


Figure 6-4. Trilinear diagram of water quality data for Upper and Lower Aquifers, Tract C-a (data from RBOSP, 1977b).

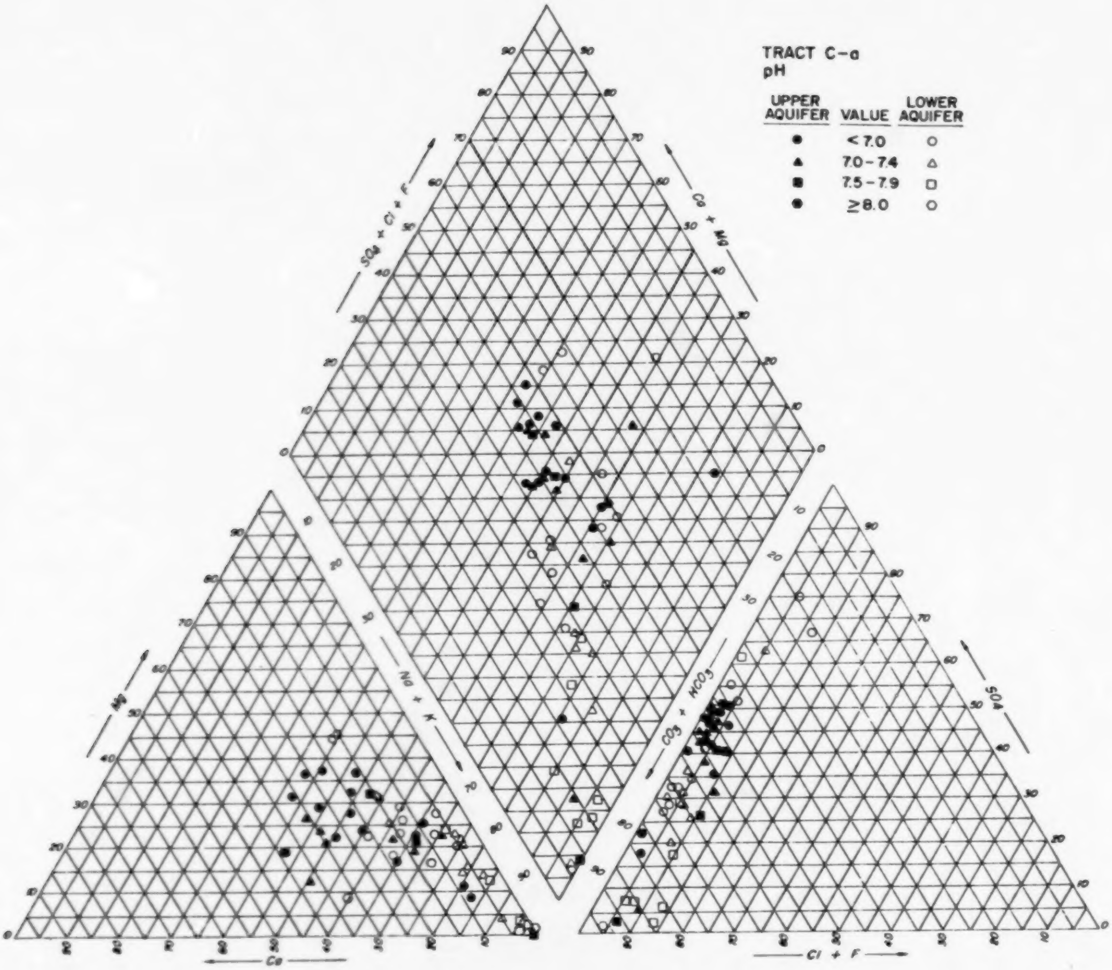


Figure 6-5. Trilinear diagram comparing inorganic composition of groundwaters to pH level, Tract C-a (data from RBOSP, 1977b).

Water Type versus TDS--

A fair correlation exists between TDS and composition, illustrated in Figure 6-6. Although most Upper Aquifer samples have a dissolved solids content below 1300 mg/l, there is little correspondence between composition variations and TDS. The correspondence in the Lower Aquifer, however, is good, with a trend of increasing TDS with increasing sodium bicarbonate content. Several Upper Aquifer wells possess a dissolved solids content above 1300 mg/l. Wells TO 3 and CE 703 both have a distinct "Lower Aquifer" composition and dissolved solids content to match. The gradient at the northeast corner of the tract where these wells are located is favorable for upward leakage. Wells G-S 10 and G-S 12 are very close to a major fault zone, but the inter-aquifer gradient does not favor upward leakage. Three Lower Aquifer wells,

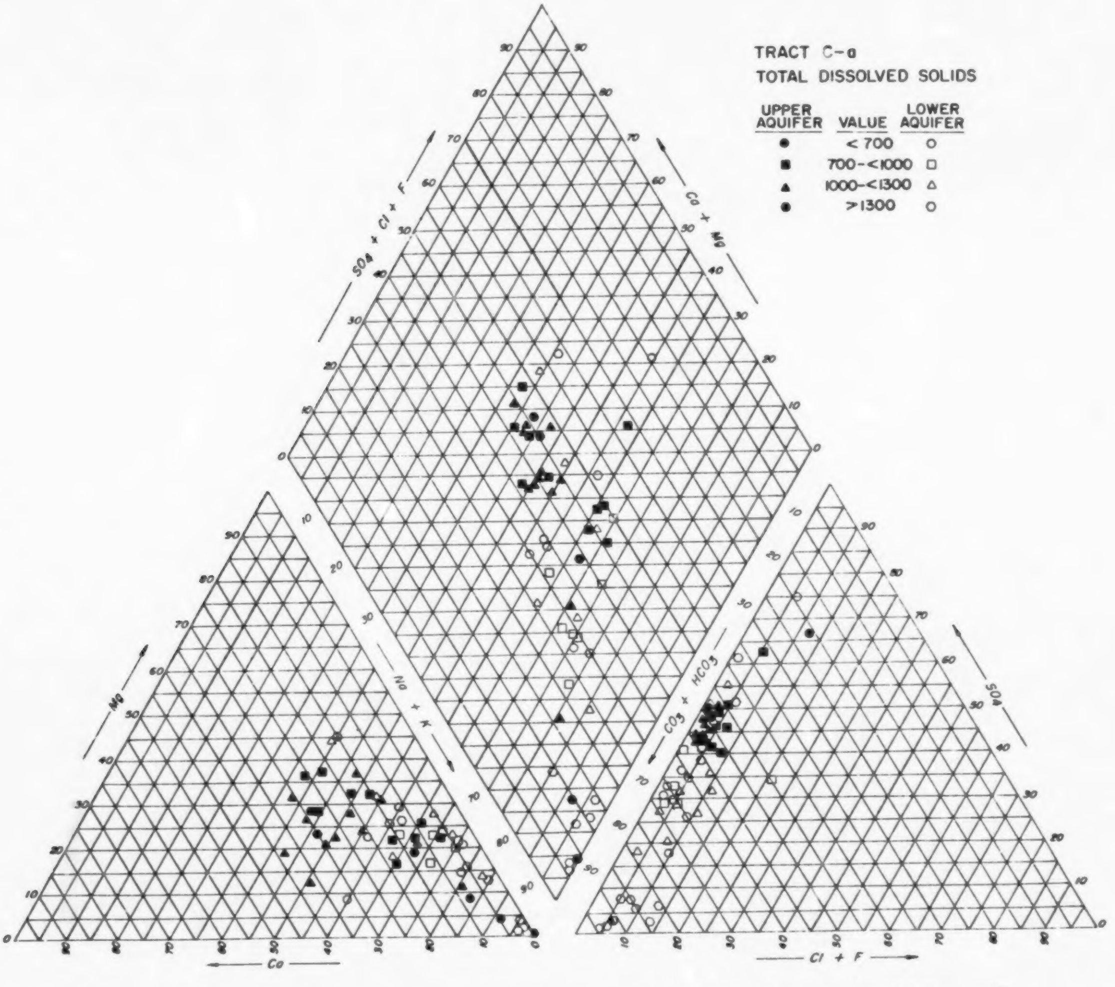


Figure 6-6. Trilinear diagram comparing inorganic composition of groundwaters to total dissolved solids concentration, Tract C-a (data from RBOSP, 1977b).

in particular CE 707, G-S 1 and CE 708, have dissolved solids below 700 mg/l. Wells CE 707 and G-S 1 are both near the same major fault and downward leakage would be occurring here. CE 709 is not near any faults. Its composition is thus anomalous.

Water Type versus Water Temperature--

The comparison of water temperature and composition in Figure 6-7 indicated a good correlation between the two. Most Upper Aquifer "type" water is below 56°C and all is below 61°C. The only Upper Aquifer wells with temperatures above 61°C are CE 702 and TO 3. This high temperature, combined with TDS and pH correlation, very strongly indicate a Lower Aquifer origin

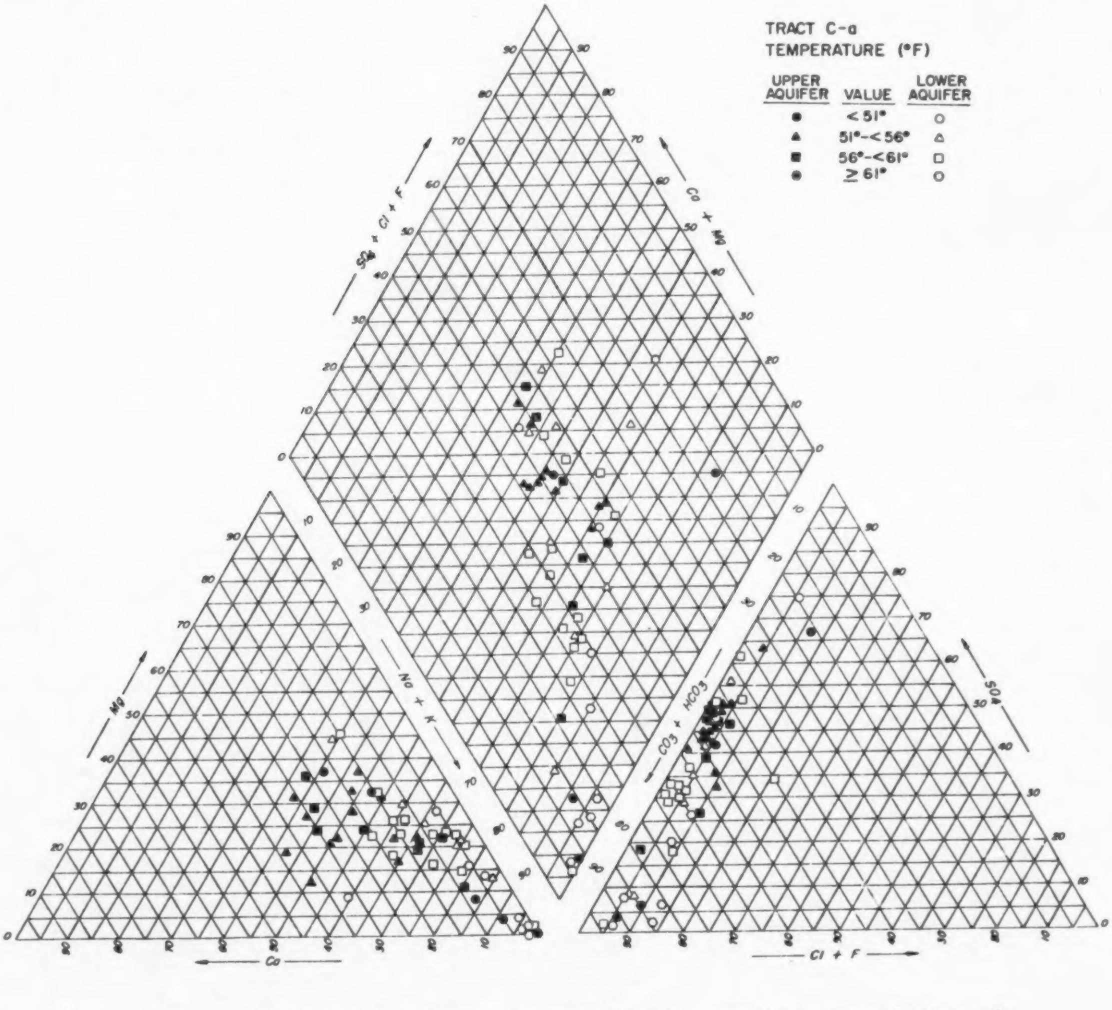


Figure 6-7. Trilinear diagram comparing inorganic composition of groundwaters to water temperature, Tract C-a (data from RBOSP, 1977b).

for the water in these wells, probably through upward leakage. Although several Lower Aquifer wells show atypically low temperatures; no pattern or correlation with TDS or pH is apparent.

Water Type versus Sampled Interval--

A correlation of water quality with interval sampling was attempted using the intervals shown in Figure 6-8. Unfortunately, few consistent relations between composition and interval could be found. This poor correlation probably is a result of the complexity of the local hydrogeology. The simple stratigraphic framework is distorted by folding and faulting. The faults serve as hydraulic barriers within aquifers and as conduits between aquifers. They also may juxtapose otherwise horizontally separated strata. The root cause of the wide variability between analyses from the same aquifer and the lack of meaningful area-wide trends is probably the inconsistent perforation with respect to the stratigraphy, but this inconsistency is vastly complicated by the structural problems.

Tract C-a water quality data have also been analyzed using statistical techniques, such as development of correlation sign matrices, varimax factor loading matrices, and discriminant function analysis (RBOSP, 1977b). Major conclusions reached were that calcium, magnesium, and sulfate were inversely correlated with the rest of the major ions and pH in the Upper Aquifer, while the rest were directly correlated. Calcium and sulfate were inversely related to bicarbonate, carbonate, fluoride, sodium, and TDS in the Lower Aquifer. The varimax factor analysis loading scores indicated the possibility of aquifer interconnection at wells CE 702 and G-S 6. Scores at wells AM 3 and G-S 12, along the rise of the Sulfur Creek Anticline, showed the same possibilities there. Possible downward leakage was indicated at holes G-S 10, G-S M1, and G-S 1. The conclusion of upward leakage at the northeast corner of the tract was strongly supported.

Comparison of Upper and Lower Aquifers

Comparison of samples from the two aquifers demonstrated that the concentration of many of the major ions is higher in the Lower Aquifer, with the exceptions of calcium (which is lower by 75 percent), magnesium (which is lower by 60 percent), and sulfate (which is lower by 65 percent). These figures support the general explanation of water quality distribution presented, as does a theoretical solubility constant analysis. This analysis showed that some Upper Aquifer samples were saturated or supersaturated with respect to calcite, but none with respect to gypsum.

Summary

In summary, the Upper Aquifer contains mostly sodium, calcium-magnesium-bicarbonate-sulfate water. The Lower Aquifer water varies from sodium-calcium-magnesium-bicarbonate-sulfate to sodium-bicarbonate. More detailed descriptions, either on an areal or stratigraphic basis, cannot be made with the present data. Upper Aquifer wells TO 3 and CE 702 are in an area of upward leakage from the Lower Aquifer. G-S 11 Upper shows many Lower Aquifer characteristics, but upward leakage seems unlikely. Lower Aquifer well G-S 1

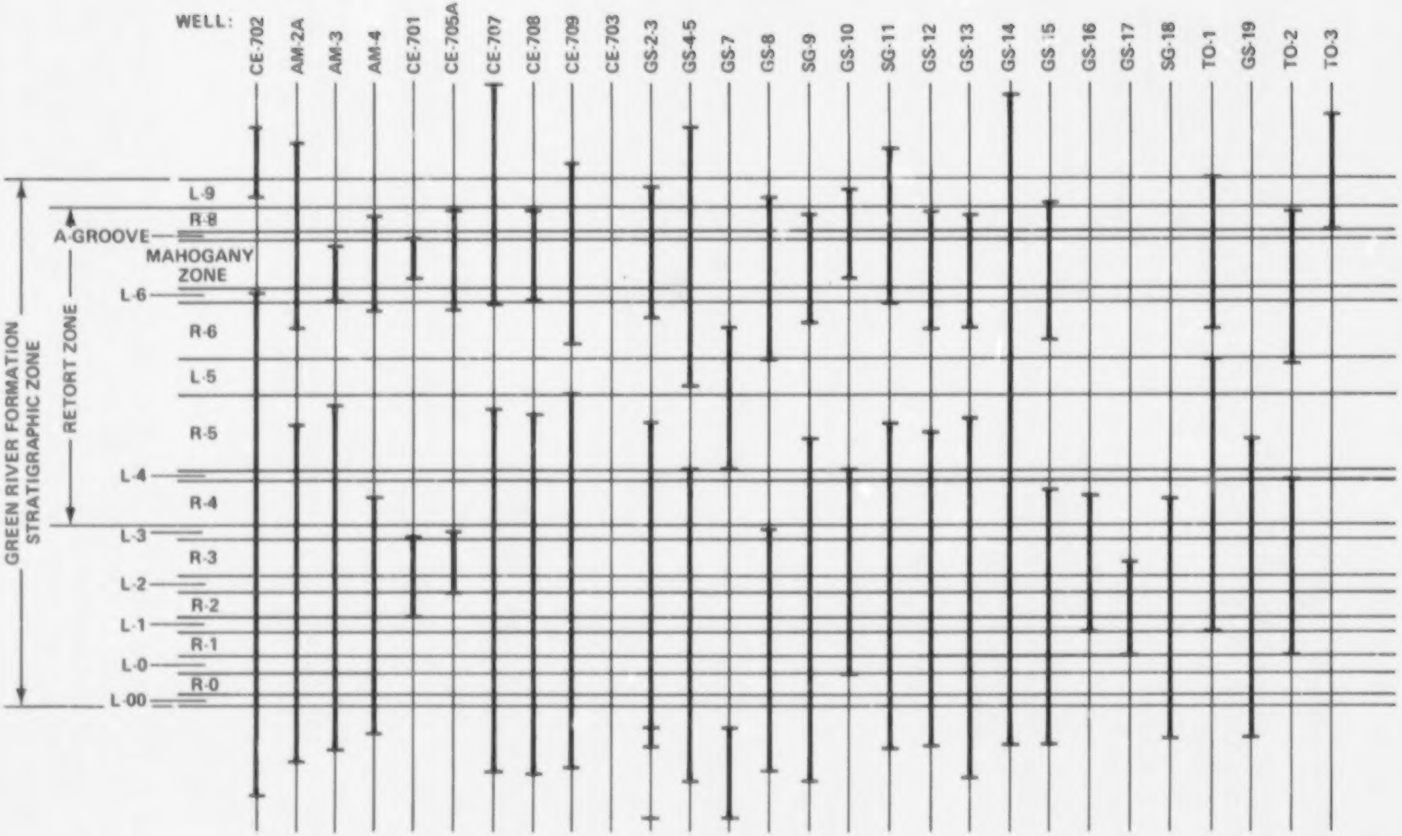


Figure 6-8. Intervals of perforation of wells on Tract C-a.

may demonstrate evidence of downward leakage from the Upper Aquifer. Upper Aquifer well TO 1 and Lower Aquifer well CE 709 are highly anomalous, without any ready explanation.

TRACT C-b GROUNDWATER QUALITY

General Description

During the course of the Tract C-b Baseline Monitoring Program, about 15 wells in the Upper and Lower Aquifers and 10 wells in the shallow alluvium were regularly monitored for water level and a wide variety of chemical constituents (C-b Shale Oil Venture, 1977b). The wells were drilled with diameters ranging from 13 to 6 inches, but several of them had as many as three strings of 2-3/8-inch tubing, perforated at selected intervals, set within the uncased well bore. These tubing strings are designated by a numeral after the well number; for example, "SG-1-2" is the second string in well SG-1. The well bores were gravel-packed after placement of the tubing. Several wells were recompleted after the original monitoring and these are designated with an "R" after the well number. More recompletions are being planned.

The intervals against which the various wells and strings are perforated or open are indicated on Figure 6-9. As previously discussed, the monitoring wells should ideally be open to identical stratigraphic intervals of the aquifer due to the highly stratified nature of the aquifer. Unfortunately, only a few of the wells and strings are actually open over the same intervals; the rest are nearly randomly spaced. This problem greatly complicates analysis of water quality distribution within the aquifer.

Alluvial well samples on Tract C-b have been collected by pumping, using a submersible pump. Deep well samples have been collected by swabbing.

In Figure 6-10, the levels of the major anions and cations are plotted on a trilinear diagram. General differences in water quality of the various aquifers are apparent. Sodium and magnesium in water from the alluvial wells both range between 30 and 50 percent, while calcium is between 15 and 25 percent. The anions are dominated by carbonate and bicarbonate (45 to 65 percent), with slightly less sulfate (35 to 55 percent), and only minor chloride.

Water quality in the springs and seeps is similar, with slight magnesium and calcium. This may be due to higher solubility of calcium carbonate because of carbon dioxide from the soil atmosphere.

Upper Aquifer water quality shows a wide variation, but the composition usually falls within the range of 50 to 90 percent sodium, 0 to 20 percent calcium, and 0 to 30 percent magnesium. The anions are dominated by bicarbonate (40 to 95 percent), with 0 to 50 percent sulfate and only 0 to 10 percent chloride and fluoride. The trend toward a higher proportion of sodium and bicarbonate is also present in water from the Lower Aquifer, which contains 90 to 100 percent sodium, and only 0 to 5 percent calcium and magnesium. Carbonate and bicarbonate compose 60 to 95 percent of the anions and sulfate only 0 to 15 percent, but chloride and fluoride are much higher, 5 to 40 percent.

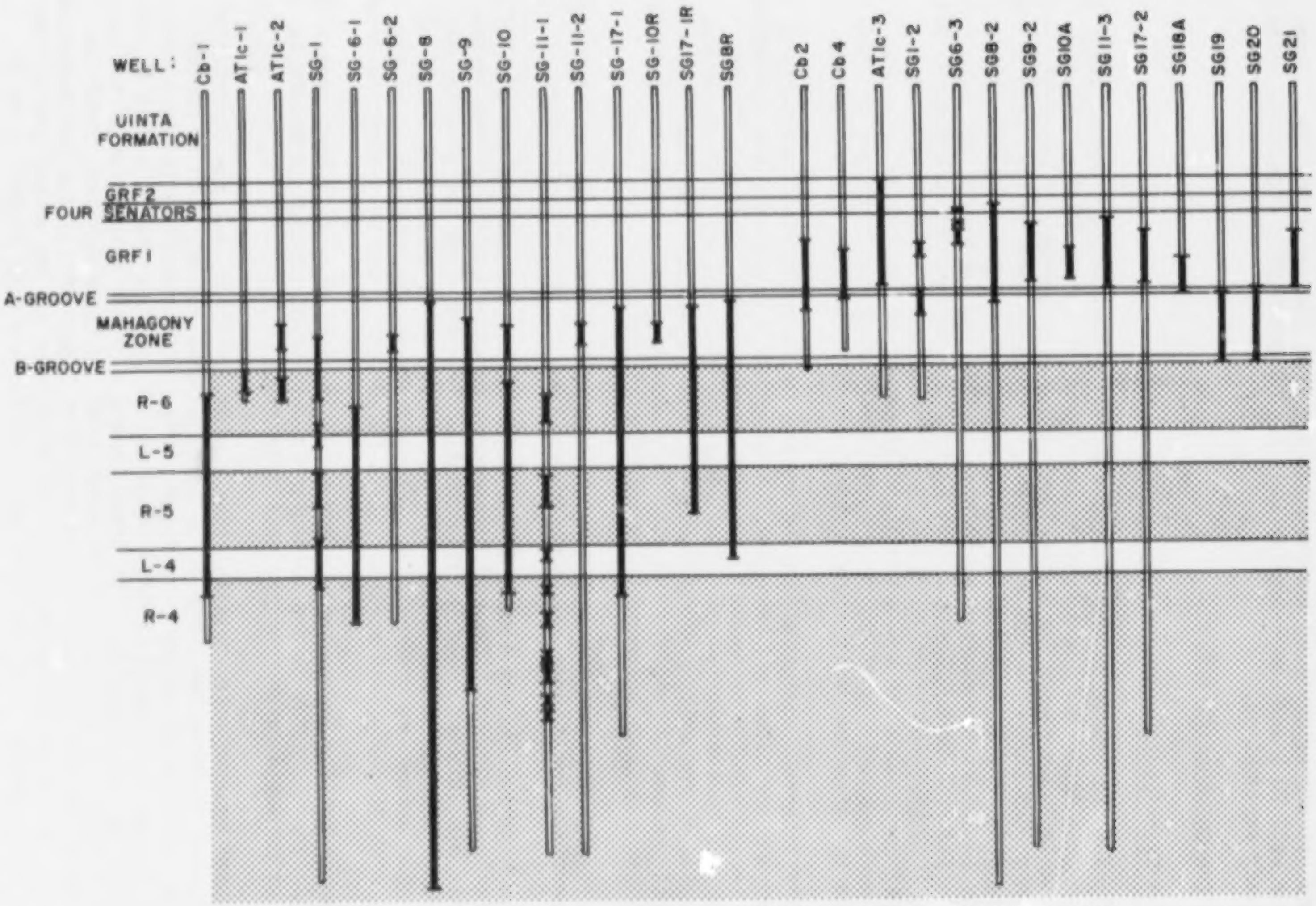


Figure 6-9. Intervals of perforation of wells on Tract C-b.

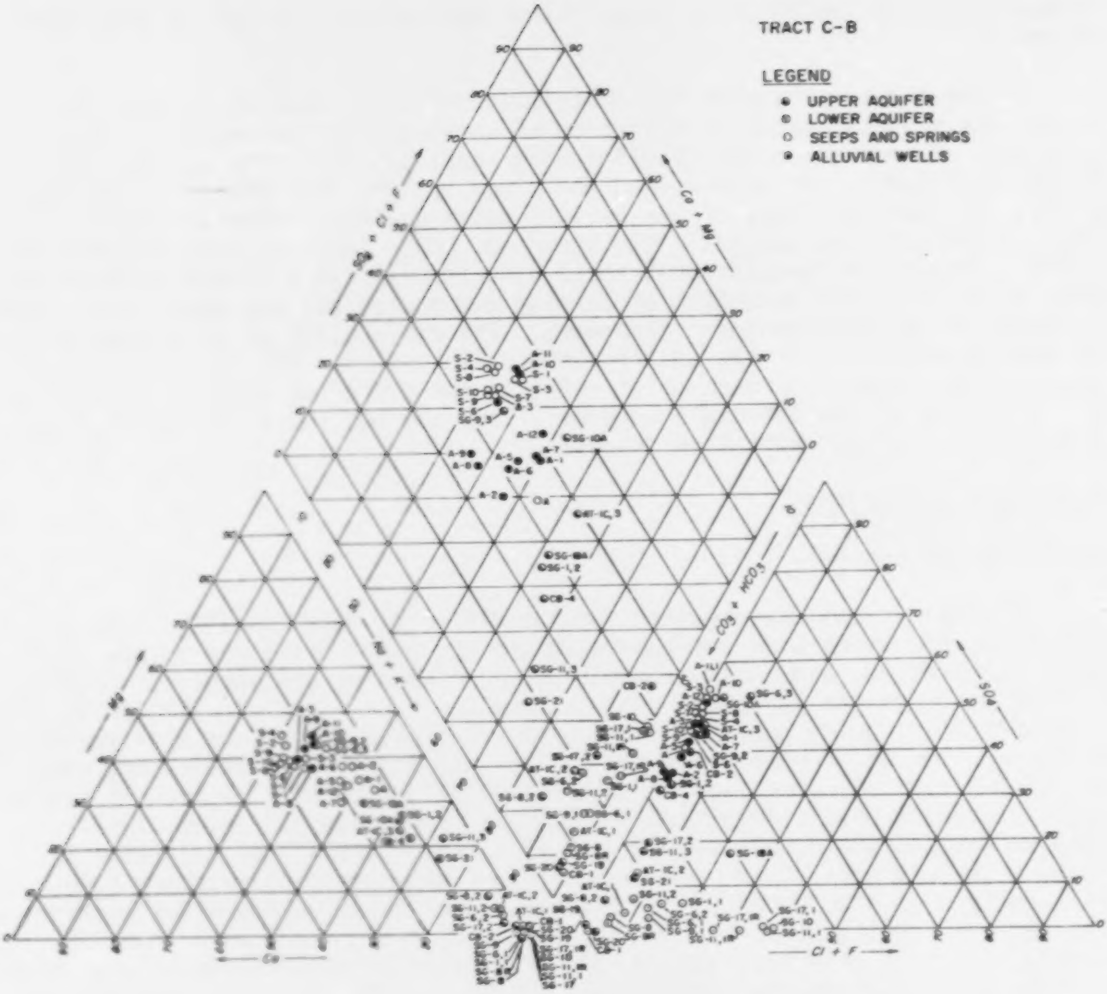


Figure 6-10. Trilinear diagram presenting groundwater quality data for Tract C-b (data from C-b Shale Oil Venture, 1977b).

The calcium and magnesium contents are probably lower because of precipitation of calcium carbonate and magnesium carbonate as bicarbonate increases due to dissolution of more soluble nahcolite. Sulfate may also be controlled by solubility of gypsum (C-b Shale Oil Venture, 1977b), but its distribution may also be a result of environmental factors. Sulfate salts are not common in the Green River Formation, and most sulfate probably originates from oxidation of sulfides during near-surface weathering. Thus, sulfate would tend to be more common in near-surface aquifers.

Water from wells, however, does not follow the pattern just discussed. In the Upper Aquifer, wells SG-17-2, Cb-2, SG-8-2, SG-19, and SG-20 more nearly resemble Lower than Upper Aquifer water quality. Well SG18A has anomalously high levels of sulfate. Lower Aquifer well SG-10R is completely anomalous.

An important portion of the description of water quality in any hydrologic system is the areal distribution of water quality parameters. This provides information on the baseline water quality conditions against which possible pollution can be measured and gives insight into processes acting within the aquifer. Maps of the various water quality parameter levels at each of the sampling points in the Upper and Lower Aquifers were prepared by TEMPO. Inspection revealed that these distributions show little relation to each other (with the exception of calcium and magnesium) and made little sense in terms of the hydrogeologic framework. The explanation of this problem lies in the inconsistency of the aquifer intervals sampled. The concentration of quality constituents at each point reflects the differing depth zones and water qualities of the intervals each well taps and not the areal differences within a single representative interval.

Water Type Comparisons

Water Type versus pH--

In order to evaluate reasons for the different water quality types encountered, the types were compared with the pH, total dissolved solids content, temperature, and interval penetrated for each of the samples. Figure 6-11 illustrates the variation of pH with water type. The correlation of type with pH is quite good, pH increasing with sodium bicarbonate as would be expected. The pH of water from all springs and alluvial wells (except one) is below 8.35. All Upper Aquifer samples below a type with 70 percent sodium and bicarbonate have a pH of between 8.35 and 8.65, and all Lower Aquifer samples (except SG-10, SG-11-1, and SG-17-1, which are all of very similar type, with less than 70 percent carbonate and bicarbonate) are above 8.65. This pattern is attributed to the dissolution of alkaline nahcolite within the aquifer. Wells SG-11-1, SG-17-1, and SG-10 (which have very high TDS levels, but high chloride, indicating dissolution of nonalkaline halite) have a lower pH. Upper Aquifer wells SG-19, SG-20, and SG-17-2 also have pH levels similar to those of the Lower Aquifer.

Water Type versus TDS--

Total dissolved solids content and composition are compared in Figure 6-12. Correlation within the Upper Aquifer, alluvial aquifers, and springs is good, all samples with less than 90 percent sodium and carbonate plus bicarbonate having a TDS content of less than 1500 mg/l. Within the Lower Aquifer, no trends are obvious. The range in TDS is very wide, ranging from 693 to 42,000 mg/l.

The presence of nahcolite-rich water over a wide range of dissolved solids contents indicates that the nahcolite does not occur in a single rich stratum, but is distributed throughout the aquifers in varying degrees. However, all of the sodium chloride-rich waters have a very high TDS, indicating a single halite-rich bed.

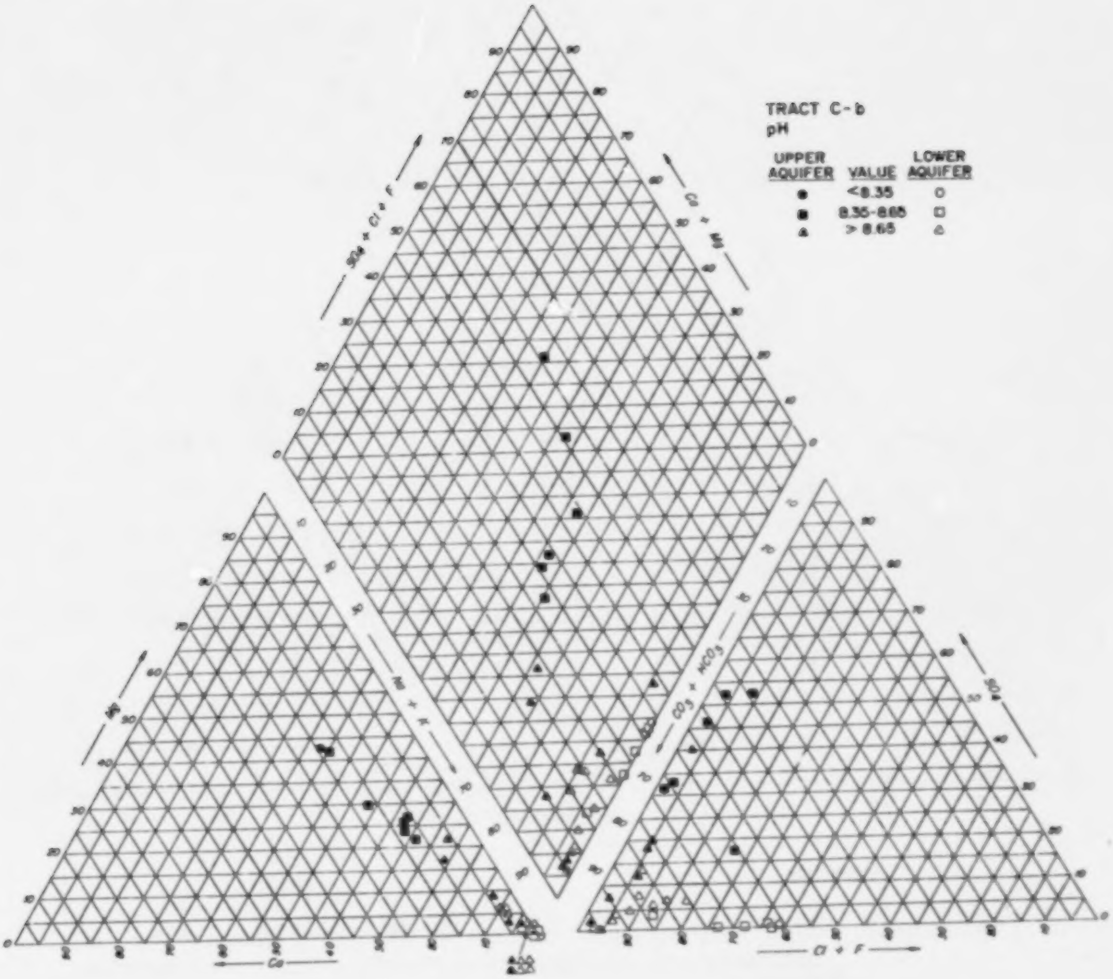


Figure 6-11. Trilinear diagram comparing inorganic composition of groundwaters to pH level, Tract C-b (data from C-b Shale Oil Venture, 1977b).

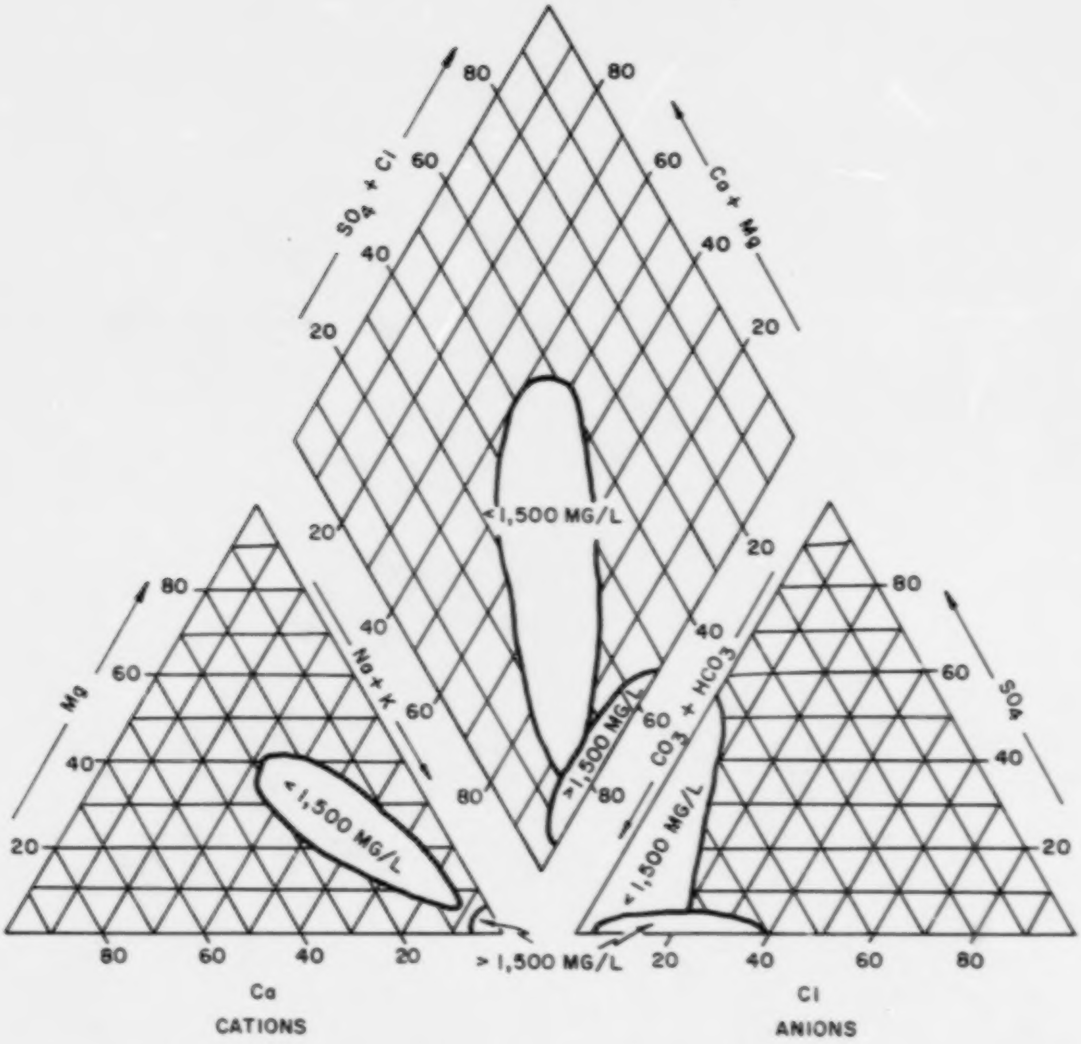


Figure 6-12. Trilinear diagram comparing inorganic composition of groundwaters to total dissolved solids concentration, Tract C-b (data from C-b Shale Oil Venture, 1977b).

Water Type versus Water Temperature--

Water temperature and composition are compared in Figure 6-13. Trends are apparent on only the broadest terms. All of the Upper Aquifer samples below 90 percent sodium carbonate plus bicarbonate are below 18°C, with the exception of SG-18A and AT-1C-3, which are below 20°C. Only samples with sodium and carbonate plus bicarbonate above 90 percent are above 20°C, and these are all Lower Aquifer with the exception of SG-19, SG-20, and SG-17-2. This is as expected, cool recharge water being warmed by the geothermal flux as it flows through deep aquifers. Water hotter than 20°C in some "Upper Aquifer" wells strongly suggests the presence of Lower Aquifer water.

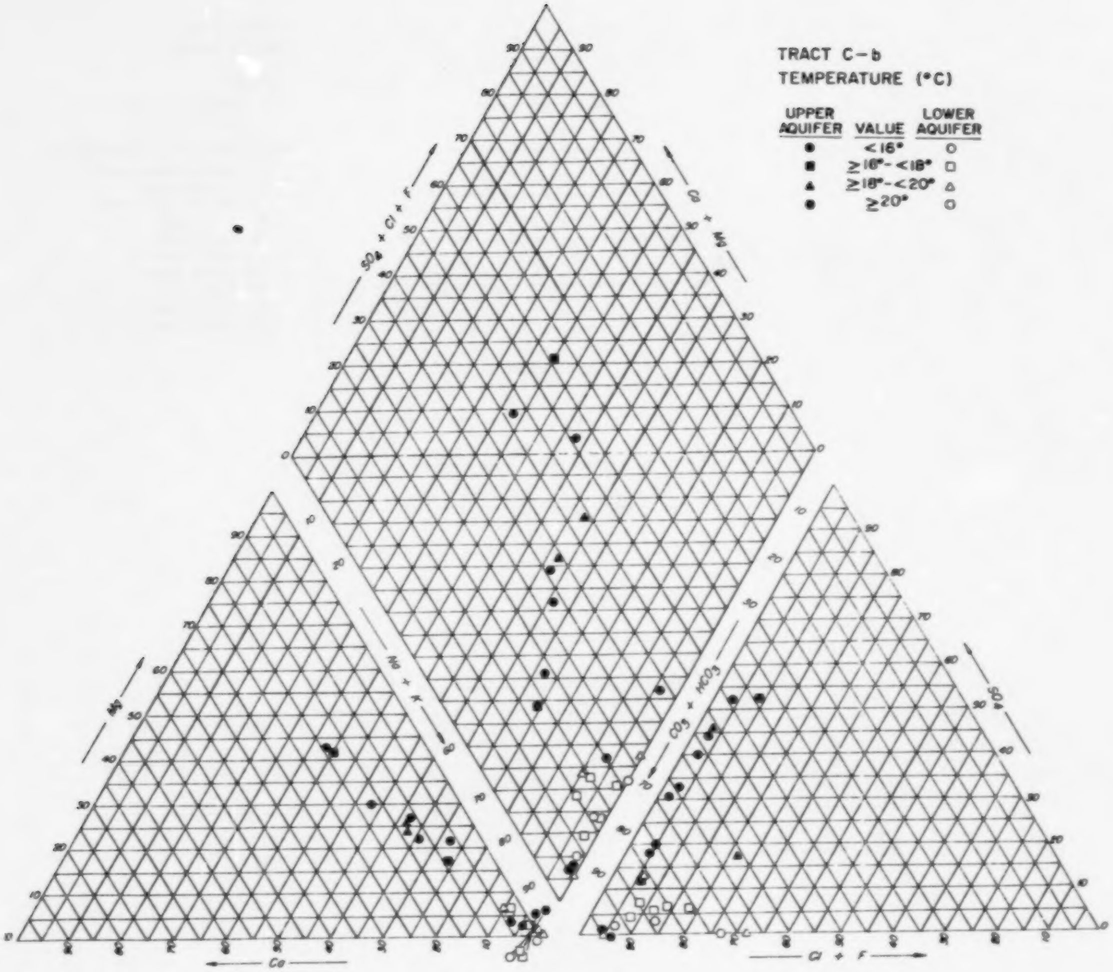


Figure 6-13. Trilinear diagram comparing inorganic composition of groundwaters to water temperature, Tract C-b (data from C-b Shale Oil Venture, 1977b).

Several Lower Aquifer wells have unusually cool water, between 16° and 18°C. These are AT-1C-1, SG-1-1, SG-6-2, SG-10R, and SG-11-2. The fact that all of these, with the exception of SG-6-1, are open to an interval just above and/or below the B-groove (the bottom of the Mahogany Zone) indicates the probability of a zone of rapid flux (shorter heating time), and thus high hydraulic conductivity in this interval.

Water Type versus Sampled Interval--

In order to obtain more information on the relationship of water quality to the stratigraphic location within the aquifer from which the water came, the aquifer was divided into stratigraphic sections, indicated on Figure 6-14.

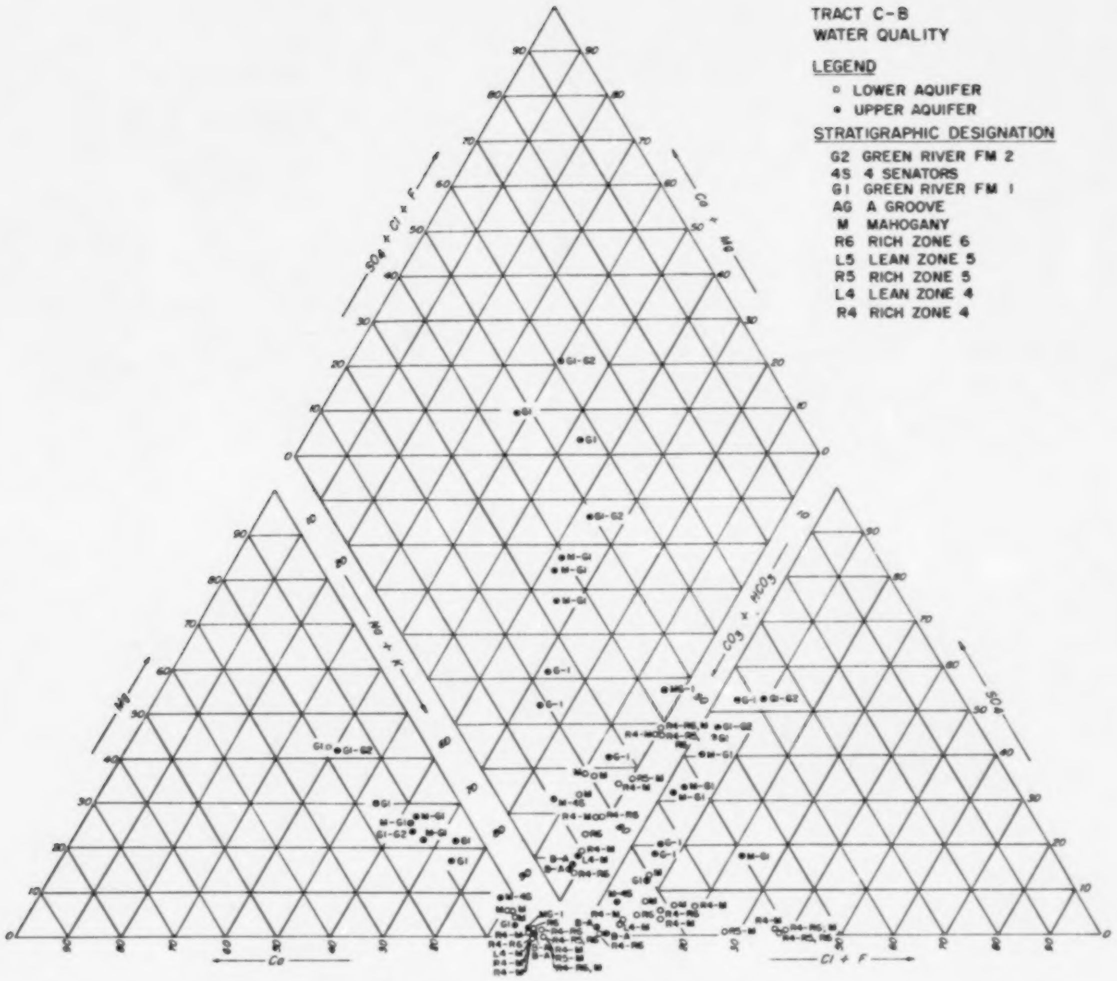


Figure 6-14. Trilinear diagram comparing inorganic composition of groundwaters to stratigraphic section, Tract C-b (data from C-b Shale Oil Venture, 1977b).

The basis of this assignment of aquifer positions is Figure 6-9. This comparison reveals a great deal about aquifer conditions.

The uppermost portion of the bedrock aquifer system from which significant data have been collected is the upper portion of the Green River Formation below the Four Senators Zone (designated GRF1 on Figure 6-9) and within the Four Senators Zone. The single well open to only this interval is SG-6-3. The data from this well indicate a composition very high in calcium, magnesium, and sulfate, compared to the rest of the deep aquifer system. TDS content is 1100 mg/l.

The remainder of the monitored portion of the Upper Aquifer extends from the upper Mahogany Zone to the middle of the GRF1 zone. Water quality from this interval is typified by SG-21, SG-11-3, Cb-4, SG-1-2, and SG-18A. The water from this interval is relatively lower in calcium, magnesium, and sulfate, with 60 to 75 percent sodium and 60 to 80 percent carbonate plus bicarbonate. Dissolved solids are lower than in the upper interval, averaging about 600 mg/l. Although several of these wells also penetrate portions of the upper interval, the water quality generally reflects origin in the lower interval, indicating a higher transmissivity in the lower interval. This conclusion is supported by the lower temperatures typical of the lower interval, and by the lower sodium bicarbonate concentration, indicating a shorter residence time. Additional confirmation comes from Tract C-b baseline studies: reported TDS levels at the end of the long-term aquifer test, which were lower than that of swabbed samples from the same well, indicating greater production from the salinity zone.

However, several wells, AT-1C-3, SG-9-2 and SG-10A, show a composition intermediate between the two, indicating mixing of waters. The inhomogeneous permeability of the fractured aquifers, as previously discussed, may explain why some wells penetrating both intervals show little mixture and others much. Two of the wells previously designated as Upper Aquifer wells (C-b Shale Oil Venture, 1977b), in fact, appear to draw water from the Lower Aquifer. In Figure 6-9, wells SG-19 and SG-20 are shown penetrating both aquifers. However, the composition of water from these wells is identical to Lower Aquifer water, the dissolved solids content is in accord with Lower Aquifer levels, and the temperature is the same as Lower Aquifer water and much higher than Upper Aquifer temperatures. Therefore, in the future, these wells will be included in the Lower Aquifer grouping.

Several wells which cannot be assigned to the Lower Aquifer nevertheless exhibit compositions similar to Lower Aquifer water. These are SG-8-2, SG-17-2, and Cb-2. Possibly, upward leakage from the Lower Aquifer is influencing these wells. SG-17-2 has a very high water temperature (temperature data are not available for the other two wells). However, the average head of the layers comprising the Upper Aquifer is somewhat higher than the Lower Aquifer over the tract, and thus upward leakage is not likely.

The zone identified as having the best water quality within the Lower Aquifer is the lower Mahogany Zone and Upper R-6. The composition is about 90 percent sodium and 80 percent carbonate plus bicarbonate, with the remainder of the anions evenly divided between sulfate and chloride. The dissolved solids are relatively low, ranging from 700 mg/l to 900 mg/l. The temperature is cooler than the rest of the Lower Aquifer, suggesting at least moderate hydraulic conductivities.

A highly saline zone about 50 feet thick was encountered in well SG-17 at about 4940 feet (RBOSP, 1977b). This zone is characterized by sodium content greater than 90 percent and relatively high chloride content (25 to 40 percent), with the remainder carbonate plus bicarbonate. Total dissolved solids are very high (20,000 to 40,000 mg/l). Water temperature is high, and the extremely high TDS probably indicates a long residence time. The transmissivity may thus be moderate to low.

Two wells, Cb-1 and SG-8, penetrate a similar interval but show radically different water quality, with carbonate plus bicarbonate content above 90 percent, and much lower TDS levels than the chloride zone, ranging from 1200 to 2500 mg/l. Temperature is fairly high. This type of water probably originates in some zone intermediate between the Lower Mahogany and the R-4, perhaps the L-5.

Several wells, notably SG-1-1, SG-6-1 and SG-9-1, have water quality compositions which seem to be some mixture of three zones. Dissolved solids range from 1300 to 4000 mg/l and composition is between that of the deep and shallower zones, as is the temperature. One well is completely anomalous, SG-10R. The extremely high chloride content of water from this well bears no resemblance to any other water from the lower Mahogany Zone, or any other water from Tract C-b, for that matter.

The general pattern of water quality distribution outlined above is confirmed by conductivity measurements of drilling water. The manner in which this was determined by tract developers is unclear. The conductivity changes with depth as shown in Figure 6-15. Above the Four Senators Zone, conductivity is greater than 1000 µmhos per centimeter, while below the zone it is less than 1000 µmhos per centimeter. The lower Mahogany Zone conductivity approximately equals 1000 µmhos per centimeter and gradually increases to about 1400 µmhos per centimeter at the R-5. Below the R-5, it increases to 3000 µmhos per centimeter.

Trace Constituents

The groundwater is rich in several trace elements. The most striking example is fluoride, which is present in concentrations as high as 190 mg/l. The mean for the Lower Aquifer is 21 mg/l and for the Upper Aquifer is 10 mg/l. This is far above the drinking water standard of 1.4 mg/l. Boron is also exceedingly high in certain strata, reaching 400 mg/l in the saline zone below the L-4. The Lower Aquifer average is 36 mg/l and the Upper Aquifer is 18 mg/l. Other trace elements which are considered high are aluminum, arsenic, copper, iron, manganese, and mercury. Other trace elements which are higher than drinking water standards in some cases are calcium, chromium, lead, nickel, selenium, silver, and zinc. Maximum, minimum, and mean values of the trace elements for the various aquifers are summarized in Tables 6-2 and 6-3. In Table 6-4, these data are compared to water quality standards.

Water in some wells on the tract contains significant organic material. This material takes the form of an oily liquid floating on the water surface, and is apparently derived from the kerogen in rich oil shale beds, although some organic contamination may occur from the swabbing equipment used for sampling. In some cases, swabbing can stimulate production of this fluid. An analysis of the liquid is presented in Table 6-5.

Summary

In summary, the aquifer system is highly stratified. Layers near the Mahogany Zone contain largely sodium bicarbonate type waters and relatively

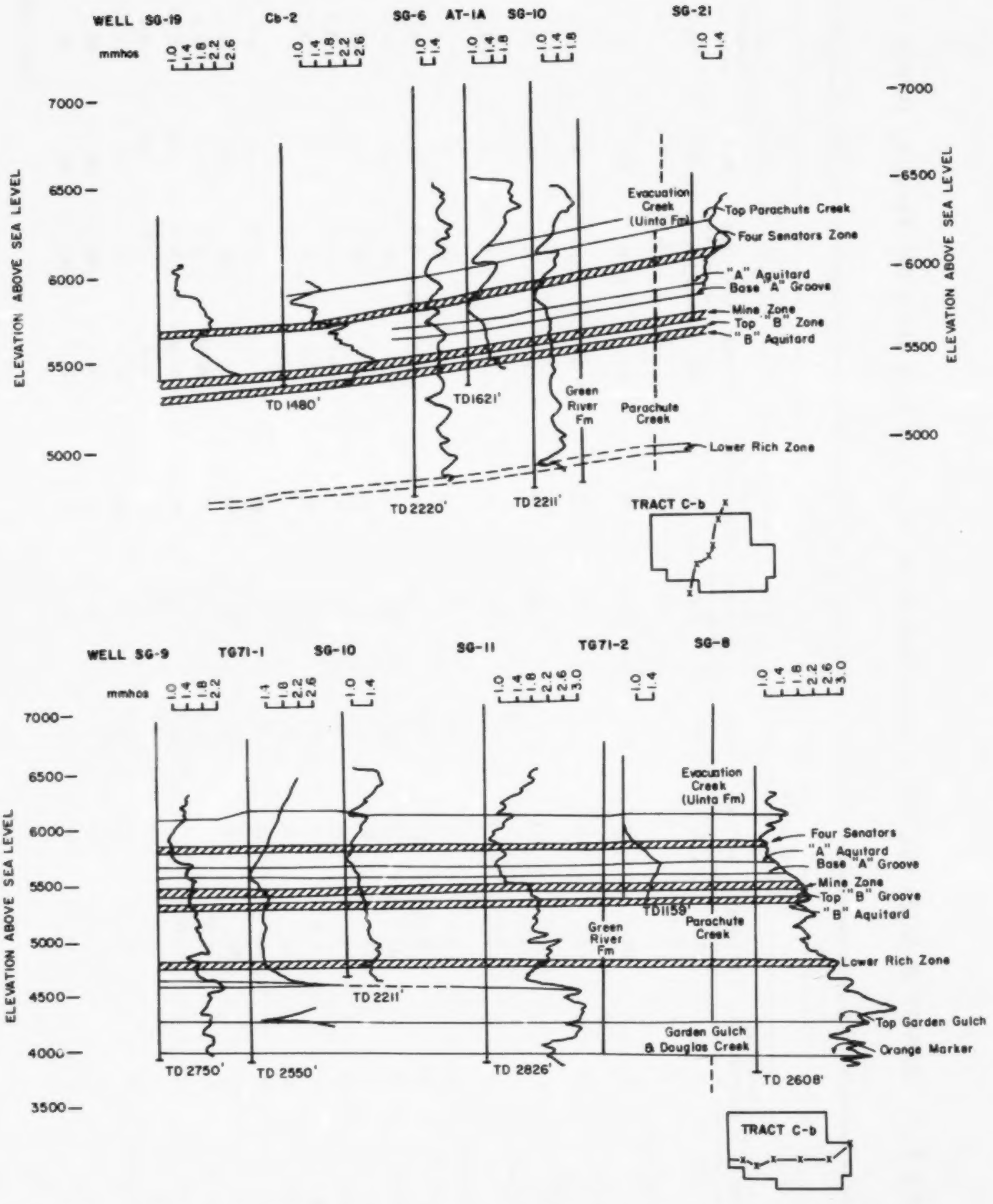

WELL SG-19
Cb-2
SG-6
AT-1A
SG-10
SG-21
mmhos
1.0 1.4 1.8 2.2 2.6
7000
6500
6000
5500
5000
ELEVATION ABOVE SEA LEVEL
-7000
-6500
-6000
-5500
-5000
Evacuation Creek (Uinta Fm)
Top Parachute Creek
Four Senators Zone
"A" Aquitard
Base "A" Groove
Mine Zone
Top "B" Zone
"B" Aquitard
TD 1480'
TD1621'
Green River Fm
Parachute Creek
Lower Rich Zone
TD 2220'
TD 2211'
TRACT C-b
WELL SG-9
TG71-1
SG-10
SG-11
TG71-2
SG-8
mmhos
1.0 1.4 1.8 2.2 2.6 3.0
7000
6500
6000
5500
5000
4500
4000
3500
Evacuation Creek (Uinta Fm)
Four Senators
"A" Aquitard
Base "A" Groove
Mine Zone
Top "B" Groove
"B" Aquitard
TD1159'
Green River Fm
Parachute Creek
Lower Rich Zone
TD 2211'
Top Garden Gulch
Garden Gulch & Douglas Creek
Orange Marker
TD 2750'
TD 2550'
TD 2826'
TD 2608'
TRACT C-b

Figure 6-15. North-south and east-west stratigraphic sections showing specific conductance profiles in selected wells on Tract C-b (C-b Shale Oil Venture, 1977b).

TABLE 6-2. SUMMARY OF WATER QUALITY OF GROUNDWATERS OF TRACT C-b (C-b Shale Oil Venture, 1977b)

	Concentration[a]									
	Alluvial wells					Springs and seeps				
Constituent	Number of observations	Minimum	Maximum	Mean	Standard deviation	Number of observations	Minimum	Maximum	Mean	Standard deviation
Conductivity	77	950	1,930	1,380	220	49	840	1,560	1,300	145
pH	77	7.3	8.7	8.2	0.3	50	7.3	8.5	8.2	0.27
Total dissolved solids	77	696	1,300	996	158	47	547	1,130	925	97
Gross alpha radiation	53	0	18	5	4	32	0	20	6	4
Gross beta radiation	53	0	13	2	4	32	0	30	4	6
Total organic carbon	31	1	9	5	3	16	1	6	3	2
Dissolved organic carbon	22	2	11	6	2	16	2	10	5	2
Ammonia	77	<0.01	15	0.5	1.8	41	0.01	0.4	0.12	0.1
Bicarbonate	77	320	730	540	90	50	320	650	480	77
Calcium	77	16	102	67	21	50	28	160	83	24
Carbonate	58	1	23	6.2	5	40	<0.1	7.2	2.9	3.3
Chloride	77	0.9	29	11	7	50	0.9	18	7.1	3.9
Hydroxide	31	<0.1	1.7	---	---					
Lithium	65	---	<0.5	---	---	45	---	<0.5	---	---
Magnesium	77	20	120	80	18	50	28	100	78	18
Nitrate	77	<0.02	9.1	1.6	2.0	45	<0.02	8.1	2.2	2.5
Phosphate	77	<0.01	1.1	<0.5	0.1	45	<0.01	0.1	<.05	0.04
Potassium	66	0.7	5	1.5	0.6	40	0.6	2.3	1.4	0.5
Silica dioxide	77	11	41	17	4	50	12	21	16	3
Sodium	77	93	730	175	86	50	68	240	130	28
Sulfate	77	200	530	370	83	50	200	440	360	66

(continued)

TABLE 6-2 (continued)

	Concentration[a]									
	Upper Aquifer					Lower Aquifer				
Constituent	Number of observations	Minimum	Maximum	Mean	Standard deviation	Number of observations	Minimum	Maximum	Mean	Standard deviation
Conductivity	52	800	4,200	1,670	700	49	630	45,000	7,240	11,800
pH	53	8.1	9.1	8.6	0.24	49	8.1	9.3	8.7	0.024
Total dissolved solids	52	520	3,100	1,100	490	49	356	42,000	6,190	11,600
Gross alpha radiation	49	0	21	6	5	43	0	460	28	83
Gross beta radiation	49	0	33	3	8	43	0	390	16	60
Total organic carbon	34	1	9	3	2	27	1	40	10	11
Dissolved organic carbon	---	---	---	---	---	21	2	175	23	38
Ammonia	51	0.1	7.9	1.2	1.3	48	0.1	200	17	42
Bicarbonate	53	340	2,100	790	525	49	100	25,000	4,000	6,700
Calcium	53	3	120	32	28	49	2	220	14	34
Carbonate	51	<1	76	21	18	47	7	2,000	220	490
Chloride	53	2	510	26	70	49	1	9,800	1,200	2,700
Hydroxide	33	---	<0.1	---	---	27	---	<0.1	---	---
Lithium	52	---	3.1	---	---	47	1.3	79	10	23
Magnesium	53	2.2	150	42	40	49	1.5	110	11	21
Nitrate	52	<0.02	2.9	0.41	0.57	49	<0.02	3.4	0.46	0.77
Phosphate	51	<0.1	0.4	<0.09	0.06	49	0.01	0.7	<0.9	0.10
Potassium	52	0.3	11	2.2	2.2	48	1	120	21	36
Silica dioxide	53	4	32	17	6	49	2	38	13	7
Sodium	53	44	1,200	330	248	49	140	17,000	2,500	4,700
Sulfate	53	4	520	220	170	49	2	350	63	92

[a] Units are in milligrams per liter, with the following exceptions: conductivity (micromhos per centimeter); pH (pH units); radiation (picocuries per liter)

TABLE 6-3. SUMMARY OF TRACE ELEMENT LEVELS IN GROUNDWATERS OF TRACT C-b (C-b Shale Oil Venture, 1977b)

	Concentration (mg/l)									
	Alluvial wells					Springs and seeps				
Constituent	Number of observations	Minimum	Maximum	Mean	Standard deviation	Number of observations	Minimum	Maximum	Mean	Standard deviation
Aluminum	47	0.01	3	0.3	0.6	33	0.004	3	0.4	0.6
Antimony	---	---	---	---	---	4	ND[a]	0.006	---	---
Arsenic	70	<0.001	0.05	0.006	0.01	45	0.0005	<0.05	0.005	0.01
Barium	50	0.01	0.6	0.07	0.1	34	0.01	0.1	0.04	0.02
Beryllium	8	ND	<0.002	---	---	5	ND	0.002	---	---
Boron	90	0.001	<0.05	0.5	0.8	37	0.001	1.6	0.4	0.5
Bromine	50	0.006	0.01	0.04	0.03	34	0.004	0.08	0.02	0.02
Cadmium	5	ND	<0.03	---	---	5	ND	<0.008	---	---
Cesium	28	ND	0.03	0.006	0.008	16	<0.001	0.02	---	---
Chromium	49	0.002	<0.1	---	---	34	0.005	0.1	---	---
Cobalt	41	<0.001	0.05	0.007	0.01	30	<0.001	0.05	0.007	0.01
Copper	50	0.005	0.2	0.04	0.04	34	0.003	0.2	0.04	0.05
Fluoride	77	0.1	5	0.65	0.87	50	0.1	2.1	0.45	0.40
Gallium	23	ND	0.003	---	---	15	ND	0.006	---	---
Germanium	6	ND	0.03	---	---	3	ND	0.008	---	---
Iodine	43	0.001	0.03	0.007	0.007	26	<0.001	0.06	0.005	0.01
Iron	77	<0.05	9	<0.3	0.5	49	0.01	7.8	<0.4	1.2
Lead	50	<0.002	0.2	0.02	0.03	35	0.001	0.05	0.02	0.02
Manganese	77	0.003	2.3	0.2	0.5	33	0.002	0.2	0.03	0.04
Mercury	41	0.00002	0.048	0.003	0.01	40	<0.00003	0.002	0.0004	0.0005
Molybdenum	41	0.005	0.2	0.04	0.03	27	<0.005	0.2	0.03	0.04
Nickel	48	0.003	0.1	0.02	0.02	33	0.003	0.08	0.02	0.02
Rubidium	50	0.002	0.06	0.01	0.01	29	0.001	0.05	0.01	0.01
Scandium	50	<0.001	0.02	0.004	0.003	34	<0.001	0.02	0.005	0.004
Selenium	21	ND	0.03	0.009	0.01	14	ND	<0.04	---	---
Silver	---	---	---	---	---	1	ND	<0.001	---	---
Strontium	76	0.04	10	1.9	1.2	49	0.6	5	2.0	1.0
Titanium	47	0.01	2	0.3	0.4	34	0.02	0.6	0.2	0.2
Tungsten	---	---	---	---	---	7	ND	0.02	---	---
Vanadium	90	<0.001	0.2	0.01	0.03	34	<0.001	0.02	0.005	0.004
Yttrium	13	ND	0.007	---	---	5	ND	0.003	---	---
Zinc	50	0.01	2	0.2	0.4	34	0.01	0.4	0.08	0.08
Zirconium	30	<0.001	0.04	0.007	0.01	19	ND	0.004	0.005	0.009

(continued)

TABLE 6-3 (continued)

	Concentration (mg/l)									
	Upper Aquifer					Lower Aquifer				
Constituent	Number of observations	Minimum	Maximum	Mean	Standard deviation	Number of observations	Minimum	Maximum	Mean	Standard deviation
Aluminum	48	0.003	4	0.3	0.7	45	0.002	2	0.3	0.4
Antimony	11	ND	0.02	---	---	24	ND	0.08	---	---
Arsenic	53	<0.001	0.06	0.01	0.01	48	0.001	0.2	0.02	0.03
Barium	51	0.009	0.6	0.1	0.1	47	0.02	8	0.8	1.7
Beryllium	14	ND	0.003	---	---	18	ND	0.002	---	---
Boron	52	0.01	18	1.4	2.6	44	6.05	400	36	100
Bromine	52	0.003	0.2	0.03	0.04	45	0.003	10	0.7	2.1
Cadmium	9	ND	<0.02	---	---	4	ND	0.1	---	---
Cesium	40	<0.001	0.2	0.01	0.03	46	<0.001	4	0.2	0.8
Chromium	50	0.002	0.3	---	---	47	0.002	0.2	<0.009	0.004
Cobalt	43	<0.001	0.01	0.003	0.003	43	<0.001	0.03	0.006	0.007
Copper	52	0.003	3	0.09	0.4	46	0.003	0.9	0.06	0.14
Fluoride	53	0.1	190	10	26	49	4	48	21	10
Gallium	33	<0.001	0.004	---	---	37	<0.001	0.06	0.007	0.01
Germanium	8	ND	0.002	---	---	15	ND	0.05	---	---
Iodine	46	<0.001	0.08	0.006	0.01	45	<0.001	3	0.3	0.7
Iron	53	<0.02	7	0.5	1.2	49	<0.05	8	0.8	1.8
Lead	52	<0.002	0.07	0.01	0.01	47	0.003	0.4	0.03	0.06
Manganese	53	0.002	0.6	0.1	0.1	48	0.002	0.6	0.1	0.09
Mercury	49	<0.00003	0.0031	0.0004	0.0008	44	<0.00003	0.0027	0.000	0.0007
Molybdenum	47	0.003	0.1	0.02	0.02	42	<0.004	0.2	0.04	0.04
Nickel	50	<0.001	0.2	0.02	0.03	30	<0.001	0.06	0.01	0.01
Rubidium	50	<0.002	0.05	0.02	0.01	47	0.005	0.9	0.07	0.2
Scandium	51	<0.001	0.009	0.003	0.002	47	<0.001	0.01	0.004	0.003
Selenium	33	<0.001	0.03	0.006	0.026	23	<0.001	0.02	0.004	0.004
Silver	12	ND	0.05	---	---	9	ND	0.02	---	---
Strontium	51	0.1	17	2.4	2.6	49	0.1	10	1.3	2.1
Thorium	4	ND	<0.001		---	1	ND	<0.001	---	---
Titanium	52	0.003	2	0.1	0.3	47	0.006	1	0.1	0.2
Tungsten	8	ND	0.02	---	---	13	ND	0.05	---	---
Uranium	13	ND	0.03		---	10	ND	0.02	---	---
Vanadium	51	<0.001	0.006	0.002	0.001	47	<0.001	0.1	0.01	0.02
Yttrium	4	ND	0.01	---	---	19	<0.001	0.03	---	---
Zinc	52	0.003	2	0.2	0.4	45	0.005	4	0.2	0.6
Zirconium	28	<0.001	0.03	0.006	0.009	36	<0.001	0.9	0.008	0.2

[a]ND - Not detected

TABLE 6-4. COMPARISON OF TRACT C-b UPPER AND LOWER AQUIFER WATER QUALITY WITH COLORADO WATER QUALITY STANDARDS (C-b Shale Oil Venture, 1977b).

	Concentration (mg/l)[a]				
Constituent	Most Restrictive Standard	Mean, Lower Aquifer	Maximum, Lower Aquifer	Mean, Upper Aquifer	Maximum, Upper Aquifer
Aluminum	0.1	0.3	2.0	0.3	4.0
Ammonia	0.5	17	200	1.2	7.9
Arsenic	0.01	0.02	0.2	0.01	0.06
Boron	0.75	36	400	1.4	18
Cadmium	0.01	---	0.1	---	0.02
Chloride	250	1,200	9,800	26	53
Chromium	0.05	---	0.02	---	0.3
Copper	0.04	0.006	0.9	0.009	3.0
Fluoride	1.4	21	48	10	190
Iron	0.3	0.8	8.0	0.4	7.0
Lead	0.03	0.1	0.4	0.01	0.07
Manganese	0.05	0.1	0.6	0.1	0.6
Mercury	0.00005	0.0004	0.0027	0.0004	0.0031
Nickel	0.1	0.01	0.06	0.02	0.2
Radiation, alpha	15	28	460	6	21
Selenium	0.01	0.004	0.02	0.006	0.03
Silver	0.00025	---	0.02	---	0.05
Zinc	0.6	0.2	4.0	0.2	2.0

[a] Except radiation, for which units are picocuries per liter.

TABLE 6-5. RESULTS OF ORGANIC FRACTIONATION ANALYSIS OF WATERS NEAR TRACT C-b (C-b Shale Oil Venture, 1977b).

Sample source	Total DOC, (mg/l)	Percent of total DOC					
		Hydrophobics			Hydrophilics		
		Acids	Neutrals	Bases	Acids	Neutrals	Bases
Well A-1	3.8	49	7	8*	36**	36**	8
Well A-3	1.8	44	28	0	28*	28*	0
Well A-6	3.5	40	23	6*	31**	31**	6*
Well A-7	2.6	23	35	8*	35**	35**	8*
Stewart Creek	16.1	6	13	0	9	72	0
Willow Creek	3.2	38	3	0	34	12	12
Upper Piceance Creek	4.5	40	9	0	20	20	11
Lower Piceance Creek	5.1	35	18	0	31	10	6
Spring S-3	2.5	32	16	8*	44**	44**	8*
Spring S-9	1.6	56	6	0	38**	38**	0
Snow at C-b-2	2.8	18	11	0	71*	71*	0
Snow at SG-18	2.0	20	5	5*	70**	70**	5*
Well SG-6-1	3.8	32	16	29*	24**	24**	29*
Well SG-6-2	3.1	26	32	16*	35**	35**	16*
Well SG-6-3	1.7	24	0	24*	71**	71**	24*
Well SG-8R	3.5	20	26	9*	46**	46**	9*
Well SG-10R	5.1	45	27	6*	22**	22**	6*
Well SG-20	2.6	54	12	27*	8**	8**	27*

*,** indicates combined total for fractions shown.

high hydraulic conductivity. Above the Mahogany Zone, dissolved solids, calcium, magnesium, and sulfate content are all higher. Deep in the Lower Aquifer are highly saline zones with extremely high dissolved solids, sodium, and chloride. Between are moderate to low hydraulic conductivity zones with largely sodium bicarbonate water.

Very little can be stated about areal distribution of water quality parameters within the aquifers due to the erratic spacing of open intervals. This spacing also severely limits the accurate determination of water quality within most of the individual strata. The confusion is compounded by the mislabeling of wells SG-19 and SG-20 as Upper Aquifer wells.

SECTION 7

POTENTIAL POLLUTANT MOBILITY

INTRODUCTION

The purpose of this section is to evaluate the potential mobility of pollutants (retort water and spent shale leachate) from MIS retorts. The general features of mobility of potential pollutants associated with surface operation and disposal sites are considered in a companion report (Slawson, 1979) and will not be repeated here.

The consideration of potential pollutant mobility in the subsurface may include evaluation of infiltration at the land surface, mobility in the vadose or unsaturated zone, and mobility in the saturated zone. Because of the above-stated focus of this discussion, and the location of the retorts within or adjacent to saturated zones, consideration of infiltration and vadose zone mobility will not be included here.

GROUNDWATER FLOW

The mobility of potential pollutants from in-situ retorts depends upon the characteristics of groundwater flow in the retort zone after retorting is completed. Such flow may be in fractures, in porous media, or in solution cavities. Flow through alluvium, rubblized oil shale, or in-situ spent shale will generally be considered as flow through a porous media. Flow in the aquifers of the Uinta Formation or Green River Formation will generally be considered as flow through fractures or solution openings. In general, far less attenuation due to sorptive processes will occur if flow is through solution openings or fractures than for flow through porous media. However, considerable dispersion and diffusion due to physical processes is possible, and interaction between leachates and natural groundwaters and certain biological processes can occur. For flow through porous media, substantial attenuation may occur for some pollutants, particularly where clays, metal oxides, or organic matter are associated with the medium.

Hydrogeologic Modifications

During development and operation of in-situ retorts, hydrogeologic conditions of the retort fields will be substantially altered. Such alteration will govern groundwater flow after retort abandonment and the release and mobility of potential pollutants from in-situ retorts. Major characteristics of in-situ operations related to the modification of the hydrogeology of the mining site and release of potential pollutants include:

- Dewatering of the retort zone and the resultant alteration of the hydraulic regime will be required at many sites.

- Mining and rubblizing the retort, which will be in the Mahogany Zone, may locally breach much, if not all, of the confining bed.

- Within the retorts, two forms of porosity and permeability will exist, the porosity and permeability of discrete solid oil shale rubble blocks and the porosity and permeability of the space within the oil shale rubble. The former will importantly affect the leaching of contaminants and the latter will control the rate of water flow through the retort.

- The mining and retorting will, to an unknown extent, probably immediately affect the porosity and permeability of rocks adjacent to the retorts as a result of the stresses caused by blasting and burning. In the longer term, sloughing and collapse of retort walls may occur and the retort roofs may stope upward, perhaps eventually reaching the surface, although the extent of surface disturbance is uncertain. Subsidence accompanying such events may further alter subsurface flow patterns.

Influence of Dewatering

Dewatering operations and the termination of dewatering will influence groundwater flow in and adjacent to the retort zone. For example, consider MIS retorts located generally within and below the various units of the Upper Aquifer, perhaps extending to the upper units of the Lower Aquifer. Dewatering is required to allow mining and retorting. As dewatering progresses and the potentiometric surface is lowered in a particular area, the aquifers will gradually be changed to unconfined aquifers and will be dewatered. At some lateral distance from the area of dewatering, the aquifers will still be confined; that is, the hydraulic head will be above the top of the aquifer.

During dewatering, hydraulic heads in certain units of perhaps the Upper and Lower Aquifer will be lowered by pumping. Head levels in adjacent aquifer units may also be affected indirectly by vertical leakage into the pumped interval. For example, dewatering in the Upper Aquifer may locally produce flow upward from the Lower Aquifer into the Upper Aquifer. As another example [using Upper Aquifer units UPC_1 and UPC_2 defined for Tract C-b (see Figure 9-6)], if UPC_2 is dewatered, downward flow from UPC_1 into the mine and retort zone may be induced. By the time dewatering is terminated, substantial mine inflow of water may occur.

When dewatering ceases, water may enter the abandoned retort zone from both lateral inflow and upward flow of groundwater from the Lower Aquifer. Water will enter from lateral inflow of groundwater from the Upper Aquifer and possibly from upward flow of water from the Lower Aquifer which, at least temporarily, will have a head level above that of the Upper Aquifer.

MOBILITY AND ATTENUATION FACTORS

Influence of Retorting Conditions

Experimental studies show that organic chemicals which are water soluble result from retorting and may be transported by groundwater (Amy, 1978). The inorganic chemistry of the retorted oil shale will also definitely be altered; however, the manner in which the inorganic chemistry of circulating groundwater will be changed by contact with the retorted shale is not yet clear.

Retorting conditions (e.g., with temperatures of 500° to 1200°C) will have an important influence on the constituents which are mobile. Under the conditions expected in an in-situ oil shale retort, several types of reactions can take place.

First, alkali earth (calcium, magnesium) carbonates can calcine in the range 500° to 800°C, for example:

$$CaCO_3 \rightarrow CaO + CO_2 \qquad (1)$$

Waters exposed to such materials will be highly basic, because of the reaction:

$$CaO + H_2O \rightarrow Ca^{++} + 2OH^- \qquad (2)$$

In addition, concentrations of HCO_3^- will decrease compared to natural groundwaters.

Organic materials may be partially or entirely oxidized during retorting, producing a wide range of species:

$$H_2O + O_2 + HC, N, S \rightarrow CO_2, NO_x, SO_2, SO_4 \qquad \text{(oxidation)} \qquad (3)$$

$$\rightarrow \text{hydrocarbons}, R\text{-}NH_2, R\text{-}CO_2, \text{ reduced polynuclear aromatics } NH_3, H_2S \qquad \text{(pyrolysis)} \qquad (4)$$

$$\rightarrow SCN^-, S_2O_3^=, S_4O_6^=, CN^- \qquad \text{(mixed)} \qquad (5)$$

The production of reduced species would be enhanced by incomplete combustion in the retort.

Normal decomposition process can also be hastened due to the fracturing and heat:

$$B_2O_3 + 6OH^- \rightarrow 2BO_3^{3-} + 3H_2O \qquad (6)$$

The latter reaction would be encouraged in basic conditions.

Transition metals with multiple oxidation states may be oxidized:

$$8OH^- \; 3O_2 + 2Mo_2O_3 \rightarrow 4MoO_4^{=} + 8H_2O \qquad (7)$$

$$8OH^- + 3O_2 + 2Cr_2O_3 \rightarrow 4CrO_4^{=} + 8H_2O \qquad (8)$$

The reactions in Equations 7 and 8 are aided by alkaline conditions, the solubility properties of both $MoO_4^{=}$ and $CrO_4^{=}$ are similar to $SO_4^{=}$.

Chalcogenic elements may be oxidized to the more soluble oxides:

$$MoS_2 + 3O_2 \rightarrow MoO_2 + 2SO_2 \qquad (9)$$

Although the mineral form of most trace elements in oil shale has not been established, Desborough et al. (1976) suggest that cobalt, nickel, copper, zinc, and possibly arsenic, selenium, molybdenum, and cadmium exist as the pyrite. Finally, sintering may occur during retorting, which would render the spent retort less permeable to groundwaters. Similarly, Smith et al. (1978) also have seen the formation of insoluble calcium and magnesium alumino-silicates during the simulated in-situ retorting of oil shale, and argued that such reactions would help insolubilize the spent shale.

Site-Specific Features

The following discussion outlines some of the features of proposed MIS developments which will influence the potential for impact of pollution sources on groundwater. The uncertainties noted in Sections 5 and 6 preclude a detailed assessment of mobility at this time.

One key factor affecting potential groundwater quality impact is the location of the MIS retort zone relative to aquifers. On Tract C-a, the retort zone was originally defined as follows (Figures 7-1 and 7-2; RBOSP, 1977a):

Retort number	Interval
1 - 4	Mahogany Marker down through middle B-groove into top of R-6 zone
5	A-groove downward to bottom of L-5 zone
6+	Top of R-8 zone to bottom of R-4 zone

On Tract C-b, the retort zone is defined as follows (Figure 7-3):

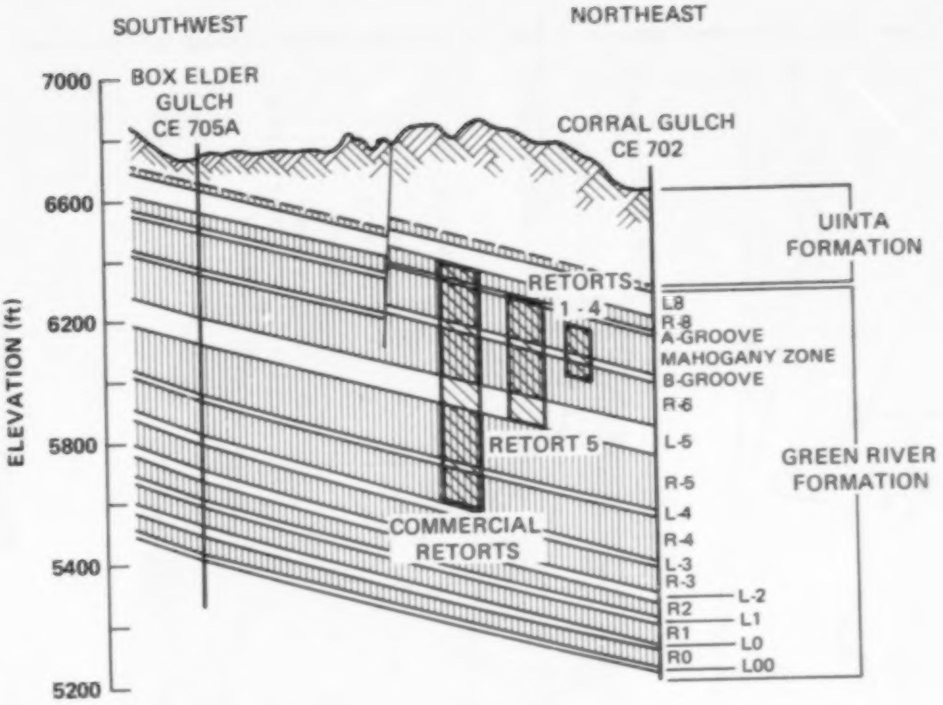

SOUTHWEST
NORTHEAST
7000
6600
6200
5800
5400
5200
ELEVATION (ft)
BOX ELDER GULCH CE 705A
CORRAL GULCH CE 702
UINTA FORMATION
RETORTS 1 - 4
L8
R-8
A-GROOVE
MAHOGANY ZONE
B-GROOVE
R-6
RETORT 5
L-5
R-5
L-4
R-4
L-3
R-3
COMMERCIAL RETORTS
GREEN RIVER FORMATION
R2
R1
R0
L-2
L1
L0
L00

Figure 7-1. Approximate location of Tract C-a retort zone in geologic cross section.

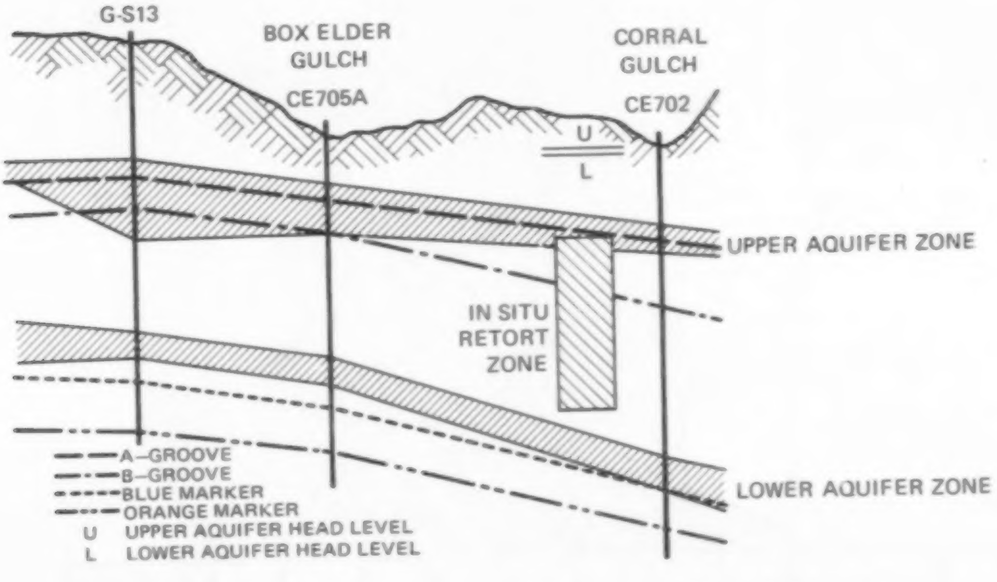
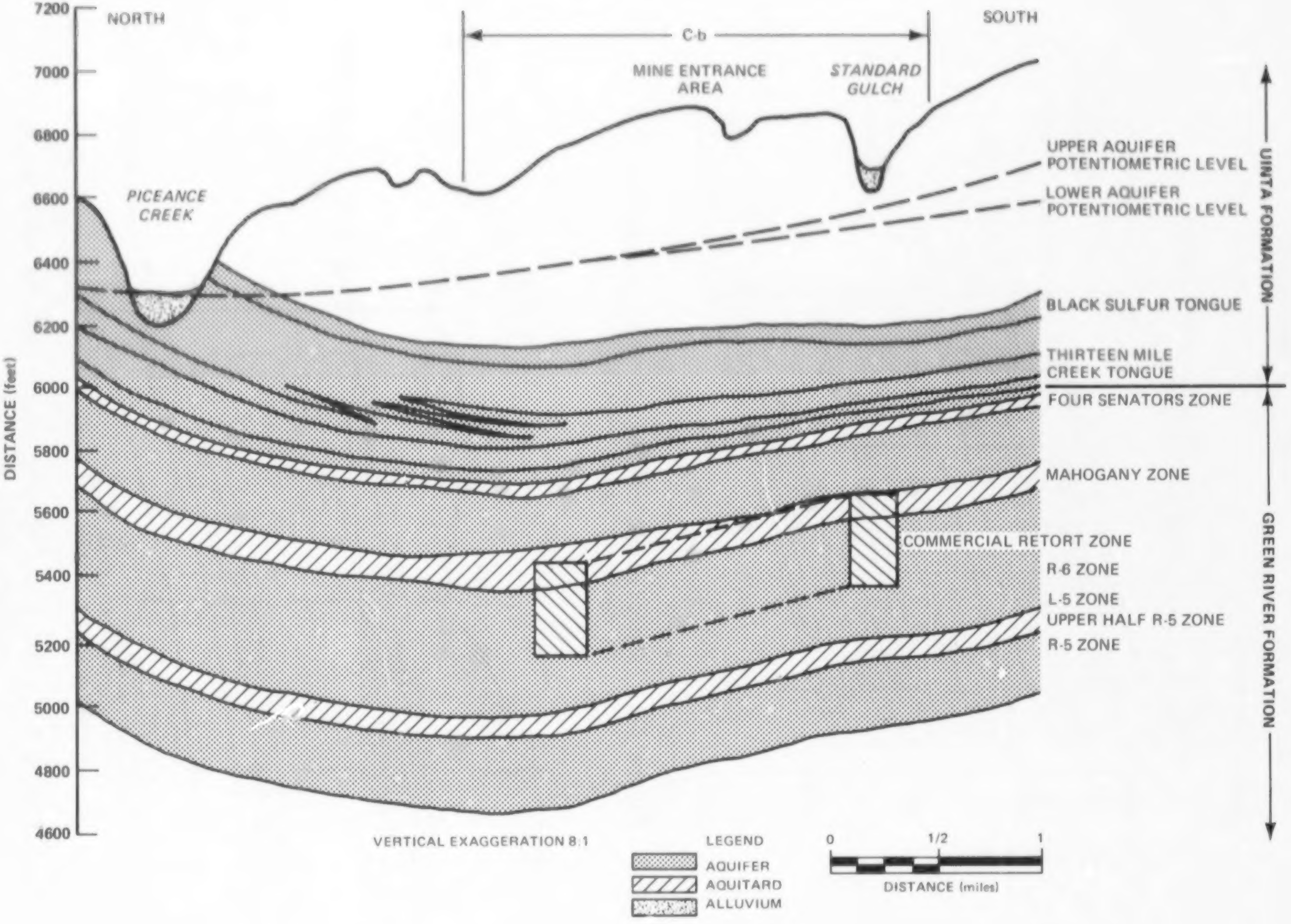

G-S13
BOX ELDER GULCH
CE705A
CORRAL GULCH
CE702
U
L
UPPER AQUIFER ZONE
IN SITU RETORT ZONE
LOWER AQUIFER ZONE
A–GROOVE
B–GROOVE
BLUE MARKER
ORANGE MARKER
U UPPER AQUIFER HEAD LEVEL
L LOWER AQUIFER HEAD LEVEL

Figure 7-2. Tract C-a in-situ retort zone in relation to geologic cross section.



7200
7000
6800
6600
6400
6200
6000
5800
5600
5400
5200
5000
4800
4600
DISTANCE (feet)
NORTH
SOUTH
C-b
MINE ENTRANCE AREA
STANDARD GULCH
PICEANCE CREEK
UPPER AQUIFER POTENTIOMETRIC LEVEL
LOWER AQUIFER POTENTIOMETRIC LEVEL
BLACK SULFUR TONGUE
THIRTEEN MILE CREEK TONGUE
FOUR SENATORS ZONE
MAHOGANY ZONE
COMMERCIAL RETORT ZONE
R-6 ZONE
L-5 ZONE
UPPER HALF R-5 ZONE
R-5 ZONE
UINTA FORMATION
GREEN RIVER FORMATION
VERTICAL EXAGGERATION 8:1
LEGEND
AQUIFER
AQUITARD
ALLUVIUM
0
1/2
1
DISTANCE (miles)

Figure 7-3. Approximate location of Tract C-b retort zone in geologic cross section.

Mine or retort element	Interval
Upper air level	Above the A-groove (above top of Mahogany Zone)
Retorts	Top of Mahogany Zone through top two-thirds of R-6 zone
Lower production level	Within L-5 zone

Figures 7-1 through 7-3 also indicate the potentiometric levels in the Upper and Lower Aquifers on Tract C-a and C-b, respectively, relative to the in-situ retorting zone. From these figures, there is obviously sufficient head in the Lower Aquifer to allow flow into the retort zone. However, flow into the Upper Aquifer zone will be controlled by the head of the Upper Aquifer and the occurrence of an interconnection between the retorts and the Upper Aquifer. Under existing head conditions, flow into the Upper Aquifer would, in general, not be expected except at locations such as the northeast corner of Tract C-a, where the Lower Aquifer head exceeds that of the Upper Aquifer. With existing head conditions generally observed on Tracts C-a and C-b, the interconnection of Upper and Lower Aquifers via abandoned in-situ retorts would result in movement of leachates into the Lower Aquifer. This assumes that existing head conditions would recur and is dependent somewhat on which aquifer reached equilibrium first after dewatering was terminated. Subsequent discharge of leachate to surface streams (such as Yellow Creek or Piceance Creek) may then occur through existing Lower Aquifer discharge points at some location(s) off tract.

Flow paths in the Upper Aquifer beneath Tracts C-a and C-b are shown in Figures 7-4 and 7-5, respectively. These are anisotropic flow nets presented in Section 5 (Hydrogeologic Framework). Difficulties arose in developing flow nets for the Lower Aquifer (see Section 5).

Retort Water Constituents

The major inorganic chemical constituents of retort water are presented in Section 3. The predominant cations would probably be sodium and ammonium. The major anions would probably be inorganic carbon forms, sulfur forms, and chloride. Of these constituents, sodium and chloride would be highly mobile. Ammonium would not generally be mobile, but it could easily be converted to nitrate and be highly mobile. However, some nitrate could subsequently be denitrified under reducing conditions and removed from solution by sulfate reduction. Both of these forms are thus classified as moderately mobile. High salinity would be a major concern. Total dissolved solids or salinity is generally considered to be mobile, because many of the major constituents are moderately or highly mobile.

Trace elements of concern include fluoride, boron, molybdenum, and possibly arsenic and barium. In general, boron and molybdenum are moderately mobile. The mobility of fluoride is controlled primarily by solubility of fluorite, and thus by the calcium content. Fluoride is also more mobile at

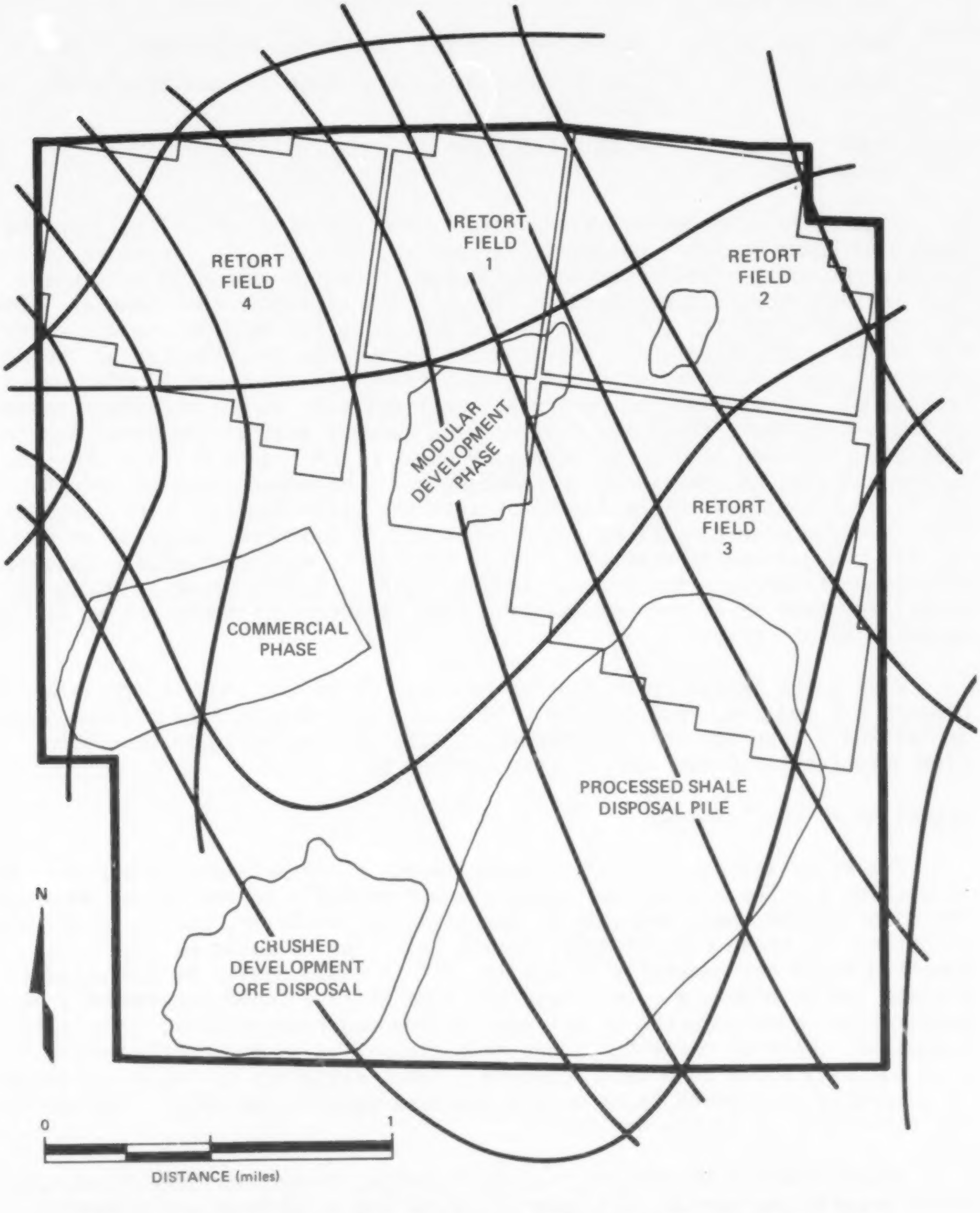

RETORT FIELD 4
RETORT FIELD 1
RETORT FIELD 2
MODULAR DEVELOPMENT PHASE
RETORT FIELD 3
COMMERCIAL PHASE
PROCESSED SHALE DISPOSAL PILE
CRUSHED DEVELOPMENT ORE DISPOSAL
N
0
1
DISTANCE (miles)

Figure 7-4. Anisotropic flow net of Upper Aquifer superimposed on Tract C-a plot plan.

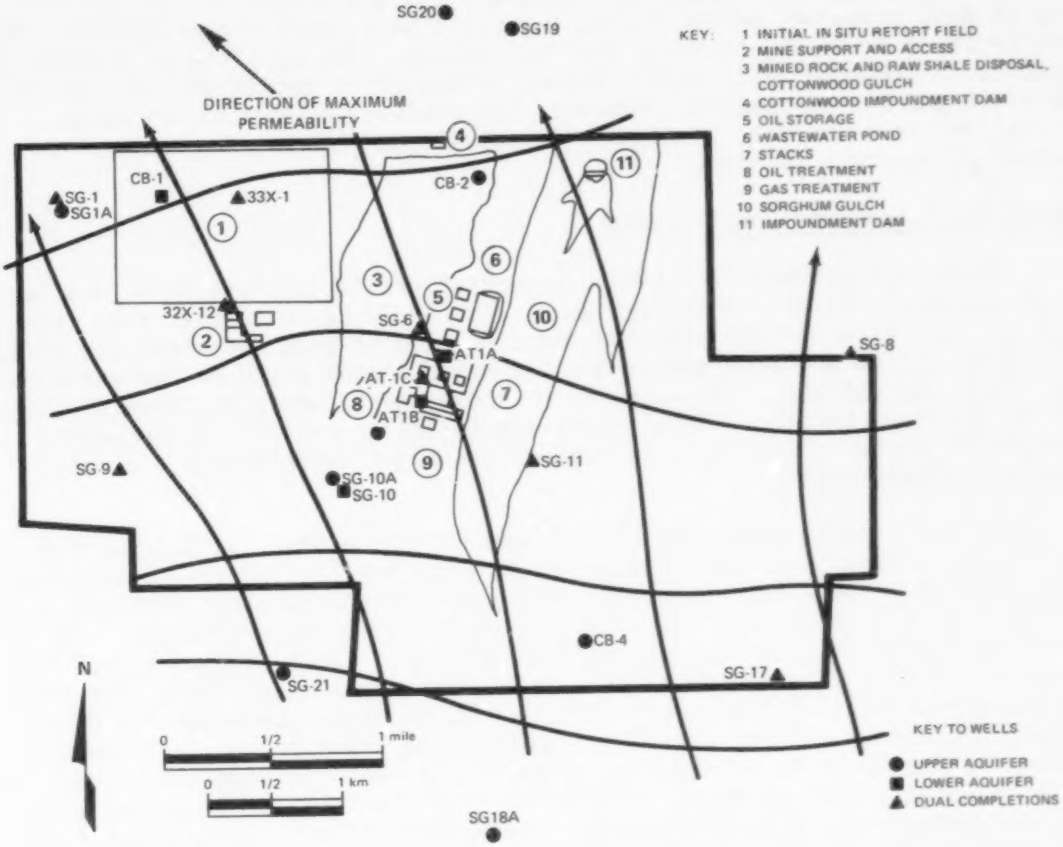

SG20
SG19
KEY:
1 INITIAL IN SITU RETORT FIELD
2 MINE SUPPORT AND ACCESS
3 MINED ROCK AND RAW SHALE DISPOSAL, COTTONWOOD GULCH
4 COTTONWOOD IMPOUNDMENT DAM
5 OIL STORAGE
6 WASTEWATER POND
7 STACKS
8 OIL TREATMENT
9 GAS TREATMENT
10 SORGHUM GULCH
11 IMPOUNDMENT DAM
DIRECTION OF MAXIMUM PERMEABILITY
SG-1
SG1A
CB-1
33X-1
CB-2
32X-12
SG-6
AT1A
AT-1C
AT1B
SG-8
SG-9
SG-10A
SG-10
SG-11
CB-4
SG-17
SG-21
SG18A
N
0
1/2
1 mile
0
1/2
1 km
KEY TO WELLS
UPPER AQUIFER
LOWER AQUIFER
DUAL COMPLETIONS

Figure 7-5. Anisotropic flow net of Upper Aquifer superimposed on Tract C-b initial development plot plan.

hign pH values. For purposes of this report, fluoride is classified as moderately mobile. However, it could be highly mobile at low calcium contents. The mobility of barium is limited by high sulfate contents, and it would thus be of low mobility. The mobility of arsenic is low except under reducing conditions. For purposes of this report, arsenic is classified as moderately mobile.

Organic chemical constituents of concern include organic carbon forms, organic nitrogen (and perhaps sulfur) forms, oil and grease, phenols, and possibly cyanide. The mobility of organic carbon forms in groundwater is poorly known; however, analyses for dissolved organic carbon content of groundwater from the Lower Aquifer at Tract C-b indicate that significant amounts are present in groundwater under natural conditions. Thus, the mobility of organic carbon forms is ranked moderate. The mobility of organic nitrogen forms in groundwater is not well known. However, it is expected that conversion to nitrate could easily occur, and this nitrogen form would be highly mobile. Some nitrate could subsequently be denitrified under reducing conditions and lost from the groundwater system. Thus, the mobility of organic nitrogen is ranked as moderate. Oil and grease are of low mobility in most granular, porous media, but could be of much higher mobility in the fracture or solution-cavity aquifer systems. The mobility of phenols and cyanide in groundwater is poorly known. Attenuation mechanisms include adsorption and biodegradation. However, the mobility of cyanide in aerobic situations is classified as high. The mobility of these constituents is ranked as moderate to high.

Spent Shale Leachate Constituents

Likely constituents and their concentrations in leachate from in-situ spent shale are discussed in Section 3. It should be noted that this information comes from surface retorted and simulated in-situ retorted materials. The major cation would be sodium and the major anions would be inorganic carbon forms and sulfate. The mobility of these constituents has been discussed in the previous section. Total dissolved solids or salinity is generally considered to be mobile, because many of the major constituents are moderately or highly mobile.

Chappel (1978) discussed trace elements of concern. Studies at the University of Colorado have focused on arsenic, boron, fluoride, molybdenum, and selenium. These trace elements were selected on the basis of their occurrence in oil shale, the likelihood of mobilization by processing, and the likelihood that they could cause serious effects. These studies showed that there was little selenium or arsenic in leachate from spent shale, but there were high contents of fluoride, boron, and molybdenum. Chromium has been found in moderate concentrations in the leachate. The primary attenuation mechanism for boron is adsorption, primarily by iron and aluminum oxides. At high pH values, such as occur in leachate from spent shale, fluoride, chromium and molybdenum, are generally mobile. Molybdenum is not highly soluble at low or moderate pH values in groundwater. Thus, fluoride, boron, and molybdenum are ranked as moderately mobile. Chromium is also ranked as moderately mobile.

Organic chemical constituents, as measured by total organic carbon, are present in significant concentrations in leachate from spent oil shale. The mobility of organic carbon forms was discussed above.

Constituents in Dewatering and Mine Water

In general, the chemical quality of water in the alluvium and from springs and seeps is similar. Water in the Upper Aquifer (at Tract C-b--UPC_1, and UPC_2 combined) is of somewhat higher salinity than groundwater in the alluvium. Contents of sodium and bicarbonate are higher, and fluoride contents are markedly higher, in the Upper Aquifer than in the alluvium. Water in the Lower Aquifer (LPC_3 and LPC_4) is locally of much higher salinity than water in the Upper Aquifer. Sodium, chloride, bicarbonate, boron, and fluoride contents are markedly higher in the Lower Aquifer. Further delineation of the vertical variation in groundwater quality may be possible after the recompletions of many of the monitor wells, as now proposed.

There are two primary potential impacts that can be considered. The first is when water from the Upper Aquifer is disposed in a manner that can affect groundwater in the alluvium or water issuing from springs or seeps. In this case, sodium, bicarbonate, and fluoride could be considered potential pollutants. The mobility of these constituents has been previously discussed. Total dissolved solids would be considered to be of moderate mobility because most of the major constituents are moderately or highly mobile. The second situation is when water from the Lower Aquifer is disposed in a manner that can affect groundwater in the alluvium, water issuing from springs or seeps, or water in the Upper Aquifer. In this case, sodium, bicarbonate, chloride, fluoride, boron, and dissolved organic carbon could be considered potential pollutants. The mobility of these constituents has been discussed above.

MODELS OF POTENTIAL POLLUTANT MOBILITY

From the preceding discussions, it is apparent that one can draw from available information on the composition of oil shale retorting byproducts; on general knowledge of physical, chemical, and biological processes; and on hydrogeologic data on the oil shale region to develop a description of the potential leaching, mobility, and attenuation of constituents from MIS retorts. It is also apparent that this description is very qualitative. This results from the many factors which are uncertain or unknown with regard to:

- Leaching phenomena in MIS retorts
- Complexities of the hydrodynamics of these groundwater systems in response to MIS development
- Influence of various attenuation mechanisms within the retort zone and elsewhere in the aquifers which may be affected by MIS development.

One approach for examining the mobility of constituents of retort water and spent shale leachate from in-situ retorts is mathematical modeling. However, because of the complexities of the existing hydrogeologic system (see Sections 5 and 6) and the additional uncertainties created by the proposed hydrogeologic modifications, (1) only very simplified models can reasonably be formulated, and (2) probably numerous models could be formulated, producing a wide spectrum of results. In addition, no data exist for validation of the models, descriptions, and predictions of the hydrodynamic and water quality processes of concern. Even with these serious limitations, models may still provide some useful information, but the limitations should always be considered in the use of the model results.

Several modeling efforts are summarized in Appendix A of this report. These efforts address relatively small-scale (a few miles) events, rather than events on a regional scale. The former approach seems more appropriate for source-specific monitoring design. These model summaries are not intended to be an all-inclusive set of available models and this listing should be updated as this program progresses.

These analyses are admittedly simplistic and numerous questions may be raised about the realism of the estimates of concentration, transport times, and attenuation processes. However, several general conclusions can be drawn from these modeling studies:

- Under certain hydrogeologic conditions (resulting from site-specific predevelopment conditions and modifications in the hydrogeologic framework (e.g., from dewatering and rubbling of in-situ retorts)), interaction between abandoned retorts and groundwater systems is likely
- Leaching of significant amounts of soluble materials is likely from some in-situ operations
- Appreciable decline in groundwater quality can result from in-situ oil shale development
- The impacts on groundwater quality may take several years to occur and have a very long duration (several decades or centuries).

The models provide some quantification of these items. Because of the numerous unknowns and complexities of this physical system, estimation of reasonable bounds on the problem may be adequate for monitoring design and evaluation purposes.

In addition, consideration of these model constructs and the assumptions inherent in the mathematical solutions provides an avenue for defining the present state of our understanding of the rather central issue of potential pollutant mobility. By defining the unknown quantities, identifying inadequate or inappropriate assumptions, and by attempting to describe extremely complex phenomena in precise mathematical form, the direction of future research is developed and plans can be formulated to develop data to deal with these difficulties.

From such considerations, the following issues have been noted:

- Model formulations addressing flow as being through porous media are not appropriate for addressing MIS development
- Significant uncertainties exist with regard to the leaching of MIS retorts (assuming interconnection with aquifers)
    - -- Variation over time (several pore volumes)
    - -- Concentrations of various constituents
    - -- Total mass leaching which may occur
    - -- Leaching rates

  - Potential influence of attenuation mechanisms within the retort zone (precipitation, sorption, ion exchange, biological activity)

  - The hydraulic properties of MIS retorts

- Significant uncertainties exist with regard to movement of constituents leached from MIS retorts

  - Hydraulic considerations

    - Aquifer interconnection

    - Differential response of aquifers after dewatering is stopped

    - Leakage between aquifers

    - Direction and rate of flow

  - Attenuation mechanisms

    - Influence of dispersion processes

    - Influence of precipitation and biological processes

    - Influence of sorption processes.

These items then become aspects for further data collection, data evaluation, and other research activities pursued to allow one to develop a better model of the impact of MIS retorts on groundwater quality. The term "model" is used here in a broad sense and is not limited to mathematical constructs, but also includes structured evaluation schemes, such as the monitoring design guidelines to be developed by this research project.

SECTION 8

PRELIMINARY PRIORITY RANKING OF POTENTIAL POLLUTION SOURCES

In the preceding sections, potential sources of impact on groundwater quality have been identified and characterized using proposed developments on Tracts C-a and C-b as the study case. The hydrogeologic framework and groundwater quality of the study area are described in Sections 5 and 6, respectively. Potential pollutant mobility from in-situ retorts is discussed in Section 7 and from surface facilities is presented elsewhere (Slawson, 1979). These descriptive and evaluative steps provide a basis for developing a preliminary priority ranking of potential pollution sources. Decisions with regard to monitoring design cost effectiveness are based on such a priority ranking.

Three basic criteria have been used to develop this source-pollutant ranking. The first criterion ranks these items relative to volume of waste, persistence, toxicity, and concentration. Certainly the source with the largest waste volume, with pollutants of longest persistence, highest toxicity and highest concentration, will receive (all other factors being equal) the highest priority for monitoring.

The second ranking criterion is based on the mobility of pollutants. Mobility is a function of method of disposal, waste loading, and sorptive and chemical interactions. The most mobile pollutants will receive a high ranking or priority for monitoring.

The third criterion in the ranking scheme addresses the known or anticipated harm to water use. This is a function of the existing or potential type and magnitude of various water uses and the concentration changes which may result from groundwater pollution.

Data from the preceding sections of this report are summarized in Table 8-1. These data have been used for development of the priority ranking, as follows:

TABLE 8-1. SUMMARY TABLE OF DATA AND ASSESSMENTS FOR POTENTIAL POLLUTION SOURCES ASSOCIATED WITH IN-SITU OIL SHALE DEVELOPMENT

Potential pollution source or cause	Amount of waste[a]		Potential pollutants (possible concentration)		Potential pollutant mobility
	Tract C-a	Tract C-b			
Waste rock and/or raw oil shale	36,000 TPD (100,000 tons storage)	41,000 TPD	See Processed Shale[b]		Relative rates for various constituents probably similar as for shale; however, absolute rates lower due to surface rather than in-situ disposal; also processed shale more leachable
Dewatering and mine water	25 cfs	4 cfs	Upper Aquifer:[c]		Major inorganic ions (e.g., sodium and chloride) measured by salinity highly mobile. Some ions, such as bicarbonates, fluoride, boron, DOC moderately mobile
			TDS	(3,100 mg/l)	
			Calcium	(1,200 mg/l)	
			Magnesium	(150 mg/l)	
			Potassium	(10 mg/l)	
			Sulfate	(520 mg/l)	
			Chloride	(510 mg/l)	
			Fluoride	(190 mg/l)	
			Boron	(20 mg/l)	
			Bicarbonate	(2,100 mg/l)	
			Carbonate	(80 mg/l)	
			Lithium	(150 mg/l)	
			Lower Aquifer:		
			TDS	(42,000 mg/l)	
			Sodium	(17,000 mg/l)	
			Calcium	(220 mg/l)	
			Magnesium	(110 mg/l)	
			Potassium	(120 mg/l)	
			Sulfate	(350 mg/l)	
			Chloride	(9,800 mg/l)	
			Fluoride	(50 mg/l)	
			Boron	(400 mg/l)	
			Bicarbonate	(25,000 mg/l)	
			Carbonate	(2,000 mg/l)	
			Lithium	(110 mg/l)	
Retort water	57,000 BPSD	27,000 BPSD	Major inorganics:[d]		Major inorganic ions (e.g., sodium, chloride, ammonia) highly mobile. Inorganic carbon and sulfur species and fluoride of more moderate mobility due to precipitation and other attenuating mechanisms. Trace constituents such as boron, arsenic, and molybdenum, of moderate mobility. Other trace constituents (e.g., barium) are of low mobility. Mobility of organic species largely uncertain; assumed to be moderate for this analysis.
			TDS	(14,000 mg/l)	
			Conductivity	(21,000 µmhos/cm)	
			pH	(9)	
			Alkalinity	(16,000 mg/l)	
			Sulfate	(2,000 mg/l)	
			Thiosulfate	(2,700 mg/l)	
			NH_3-N	(3,800 mg/l)	
			NH_4^+-N	(3,500 mg/l)	
			Chloride	(750 mg/l)	
			Sodium	(4,300 mg/l)	
			Fluoride	(60 mg/l)	
			Organics:		
			DOC	(1,000 mg/l)	
			Organic N	(630 mg/l)	
			Phenols	(60 mg/l)	
			Cyanide	(1 mg/l)	

(continued)

TABLE 8-1 (continued)

Potential pollution source or cause	Amount of waste[a]		Potential pollutants (possible concentration)	Potential pollutant mobility
	Tract C-a	Tract C-b		
Retort water (continued)			Trace elements:	
			Arsenic (1 mg/l)	
			Barium (1 mg/l)	
			Boron (30 mg/l)	
			Bromide (2 mg/l)	
			Iron (1 mg/l)	
			Molybdenum (0.5 mg/l)	
			Selenium (0.2 mg/l)	
Processed shale:				
In-situ (leachate)	9.8 to 14.4 x 10^8 tons (total)	1.5 to 2.2 x 10^9 tons (total)	Major inorganics:[e]	Major inorganics (e.g., sodium) as measured by TDS highly mobile. Mobility of inorganic sulfur and carbon species and fluoride may be moderated by precipitation reactions. Trace constituents (e.g., chromium, molybdenum, and boron) of moderate mobility. Other trace elements probably low mobility. Mobility of organics uncertain.
			TDS (30,000 mg/l)	
			pH (9)	
			Bicarbonate (9,800 mg/l)	
			Carbonate (2,000 mg/l)	
			Sulfate (4,800 mg/l)	
			Nitrate (5 mg/l)	
			Chloride (4,300 mg/l)	
			Fluoride (50 mg/l)	
			Calcium (60 mg/l)	
			Magnesium (230 mg/l)	
			Sodium (8,900 mg/l)	
			Potassium (35 mg/l)	
			Boron (>40 mg/l)	
			TOC: (40 mg/l)	
Surface disposal (leachate)	36,000 TPD	None	Major inorganics:[f]	See Slawson (1979)
			TDS (140,000 mg/l)	
			Sodium (35,000 mg/l)	
			Calcium (3,000 mg/l)	
			Magnesium (4,700 mg/l)	
			Potassium (600 mg/l)	
			Sulfate (90,000 mg/l)	
			Chloride (3,000 mg/l)	
			Fluoride (20 mg/l)	
			Organics:	
			Phenolics Unknown	
			TOC (3-5 w/o)	
			Benezene extractables (POM, PAH) (2,500 ppm possibly)	
			Carcinogens Unknown	
			Trace elements:	
			Mercury (0.005 mg/l)	
			Lead (0.004 mg/l)	
			Cadmium (0.006 mg/l)	
			Arsenic (0.2 mg/l)	
			Copper (0.2 mg/l)	
			Zinc (3 mg/l)	
			Selenium (2 mg/l)	
			Iron (2 mg/l)	
			Boron (10 mg/l)	

(continued)

TABLE 8-1 (continued)

Potential pollution source or cause	Amount of waste[a]		Potential pollutants (possible concentration)	Potential pollutant mobility
	Tract C-a	Tract C-b		
Oily water	Water ~57,000 BPSD	Water ~27,000 BPSD	See Retort Water	
Foul water stripping	Uncertain, see oily water treatment		See Retort Water	
Raw water treatment	Sludge 870 TPY Zeolites 3 TPY	Uncertain	Major inorganic salts	Soluble inorganics high mobility. Trace element mobility low.
Cooling water blowdown	Uncertain	100 gpm	See Dewatering Water; concentrations expected to increase significantly	Soluble inorganics of high mobility. Trace elements low to moderate mobility.
Sanitary waste water	Uncertain	Uncertain	Similar to Groundwater Quality; increased nitrates, biochemical oxygen demand	See Cooling Water Blowdown.
Oil treatment and upgrading	No on-site upgrading except addition of flow-enhancing agents		Not applicable, except for spill potential	
Sulfur recovery process	265 TDPD	92.2 LTPD	Sulfur species	Moderate to low mobility if spilled or otherwise exploded.
Catalysts for sulfur recovery	52 TPY	Uncertain	Not applicable to local conditions, material returned to manufacturer	
Tankage: Shale oil Naphtha Heavy oil Gas oil Fuel oil Ammonium-nitrate	 50,000 bbl 70,000 bbl 140,000 bbl 1,000 bbl 21,000 bbl 525 tons	Uncertain	Miscellaneous organics:[g] Fuels Oil and grease Numerous hydrocarbons Ammonium-nitrate	
Runoff	Variable	Variable	Soluble salts (uncertain) Organics from process area (uncertain)	Soluble salts highly mobile. Trace elements, organics probably low mobility.
Disturbed areas	1,759 acres	1,456 acres	Soluble salts (uncertain)	See Runoff
Explosives	52 TPD explosives used; amount of residue unknown	Uncertain	Ammonia (uncertain) Nitrates (uncertain) Fuel oil (uncertain)	Inorganics probably of high mobility. Organics largely uncertain.

[a] Maximum or total amounts used for full commercial operation.

[b] Constituents of importance are probably the same, although levels (concentrations) for raw shale are probably appreciably lower than for spent shale.

[c] From Table 6-2, Tract C-b water quality data, maximum concentrations (numbers rounded)

[d] From Table 3-2 (numbers rounded)

[e] From Table 3-6 (numbers rounded)

[f] From Slawson (1979); study of surface retorting and disposal operations proposed for Lease tracts U-a and U-b.

[g] Concentration uncertain, release dependent on spill events.

- Preliminary ranking with regard to size of source:

  Solid wastes

  1. In-situ spent shale
  2. Surface disposal of spent shale
  3. Waste rock, raw shale
  4. Sulfur
  5. Ammonium nitrate stockpile
  6. Wastes from raw water treatment
  7. Catalysts from sulfur recovery
  8. Explosives residues
  9. Disturbed areas

  Liquid wastes

  1. Mine water, dewatering
  2. Retort water
     -- oily water treatment
     -- foul water stripping
  3. Cooling tower blowdown
  4. Oil and fuel tank storage
  5. Runoff from facilities
  6. Sanitary waste water
  7. Oil treatment and upgrading

- Preliminary ranking with regard to potential pollutant concentration, toxicity, etc.:

  Solid wastes

  1. In-situ spent shale
  2. Surface disposal of spent shale
  3. Sulfur
  4. Ammonium nitrate stockpile
  5. Waste rock, raw shale
  6. Explosives residues
  7. Wastes from raw water treatment
  8. Catalysts from sulfur recovery
  9. Disturbed areas

  Liquid wastes

  1. Retort water
     -- oily water treatment
     -- foul water stripping
  2. Oil and fuel tank storage
  3. Oil treatment and upgrading
  4. Cooling tower blowdown
  5. Mine water, dewatering
  6. Sanitary waste water
  7. Runoff from facilities

These listings lead to the following composite first criterion ranking:

Relative ranking	Potential pollution source
Highest	In-situ spent shale disposal
	Surface spent shale disposal
	Retort water
Intermediate	Waste rock, raw shale
	Sulfur
	Mine water, dewatering
	Cooling tower blowdown
	Oil and fuel tank storage
	Ammonium nitrate stockpile
Lowest	Oil treatment and upgrading
	Runoff from facilities
	Sanitary waste water
	Raw water treatment wastes
	Catalysts from sulfur recovery
	Explosives residues
	Disturbed areas

To evaluate the potential mobility of groundwater pollutants, consideration must be given to attenuation mechanisms. These, together with types of pollutants affected, are as follows:

Mechanism	Application
Filtration	Suspended material, algae, and large bacteria
Adsorption	Bacteria, viruses, and certain trace elements, organics
Biological degradation	Organic constituents
Chemical reactions	Certain inorganic constituents
Dispersion	Constituents not removed by other mechanisms
Precipitation	Major inorganic, trace element, and organic constituents

It should be noted that dispersion is a diluting mechanism. It does not physically remove pollutants, and it is applicable to all pollutants which are not attenuated by other mechanisms.

A preliminary ranking with regard to potential pollutant mobility is presented below.

Solids

1. In-situ spent shale
2. Surface disposal of spent shale
3. Ammonium nitrate stockpile
4. Explosives residues
5. Wastes from raw water treatment
6. Catalysts from sulfur recovery
7. Sulfur
8. Waste rock, raw shale
9. Disturbed areas

Liquids

1. Mine water, dewatering (assumed reinjected)
2. Retort water (some brought to surface, some remains in situ)
3. Cooling tower blowdown
4. Sanitary waste water
5. Oil and fuel storage
6. Runoff from facilities
7. Oil treatment and upgrading

This ranking is based upon the predominant type of pollutants in the various solid and liquid wastes. But equally important is how the waste reaches groundwater. Those wastes released at the ground surface must travel farther and there is more opportunity for attenuation than do wastes released underground in direct contact with groundwater.

For the purposes of this preliminary ranking and because of the low rate of groundwater use close to the oil shale tracts, the first criterion priority ranking developed above will be used here to express the possible hazards to potential water users (third criterion ranking). Priorities with regard to this criterion can be expected to be quite site-specific and variable.

From the preceding discussions, a preliminary ranking of potential pollution sources has been developed (Table 8-2). Uncertainties or information voids exist in the data base used to develop this ranking. This is particularly true in the areas of potential pollutant characterization and the mobility of various major inorganic ions, trace elements, and organic species to be encountered in oil shale development. In addition, site-specific development plans and hydrogeology may result in modification of this ranking for specific applications. Thus, professional judgment plays a significant role in the development of Table 8-2.

This priority ranking serves as a general basis for the design of monitoring plans for modified in-situ oil shale developments, such as proposed for Tracts C-a and C-b. Specific monitoring plan designs are addressed

TABLE 8-2. PRELIMINARY PRIORITY RANKING OF POTENTIAL POLLUTION SOURCES

Relative ranking	Potential pollution source
Highest	In-situ spent shale disposal
	Surface disposal of spent shale
	Retort water
	Mine water, dewatering
Intermediate	Sulfur
	Cooling tower blowdown
	Ammonium nitrate stockpiles
	Explosives residues
	Oil and fuel tank storage
Lowest	Waste rock, raw shale
	Sulfur
	Oil treatment and upgrading
	Sanitary waste water
	Raw water treatment
	Runoff from facilities
	Catalysts from sulfur recovery
	Disturbed areas

through evaluation of existing monitoring programs, identification of alternative monitoring approaches, and the selection of a monitoring program for field implementation which addresses defined monitoring needs.

These considerations are presented in Sections 9, 10, and 11 of this report using Tracts C-a and C-b as example cases. These discussions are used to illustrate the monitoring design process which is a framework for decision-making based on cost-effectiveness considerations. The framework presented here is preliminary, largely due to the site-specific nature of the evaluations, the absence of any testing or validation of recommendations at this time, and only qualitative consideration of costs. In the second phase of this project, preliminary results provided here will be tested and modified as needed to develop monitoring design recommendations more generally applicable to the modified in-situ process.

SECTION 9

EVALUATION OF EXISTING MONITORING

The results of baseline data collection programs on Lease Tracts C-a and C-b are presented in Sections 5 and 6 of this report as example cases of available data bases used for design of groundwater quality monitoring programs. This section presents an evaluation of operational monitoring programs which were proposed by the tract developers.

The monitoring programs described are those employed or planned by tract developers at the time of drafting this report. This description is provided to define the general nature of these monitoring programs. The details of developer monitoring programs may be modified from time to time by tract developers or regulatory agencies. Recent modifications may not be included in the following description.

TRACT C-a MONITORING

Monitoring data collected during the Tract C-a MDP (Tables 9-1 and 9-2) will be compared with baseline data using statistical methods, such as frequency, scattergram, bivariant correlation, factor, discriminant function, and trend analyses. These analyses are intended to identify anomalies and to allow identification of the cause of the anomaly, such as changes in baseline hydrology or environmental impact, largely by assessing water quality exceeding expected fluctuations defined during the baseline studies.

Observation of such unexpected fluctuations will lead to efforts to determine if tract development caused the observed changes. Subsequently, sample collection will be implemented to determine the type of contaminant and to trace the source.

The hydrologic monitoring program includes sampling of surface waters at spring and seep stations, at surface gaging stations, and at impoundments. The rationale for the programs is summarized as follows:

- Springs and seeps program (Figure 9-1)
  - -- Four of the springs and seeps were concluded to be hydraulically connected with the Upper Aquifer
  - -- Monitoring operation:
    - • If unexpected are flows observed, water quality will be sampled

TABLE 9-1. SUMMARY--PROPOSED HYDROLOGY MONITORING PROGRAM, TRACT C-a

	Continuously	Quarterly	Semi-Annually	Other
SURFACE WATER:				
Stream gaging stations[a] (Figure 9-1)				
DOC fractionation (once initially)				
Conductivity	x(6)			
Temperature	x(6)			
Flow	x(6)			
Limited water quality		x(6)		
Baseline water quality			x(6)	
Springs and seeps[a] (Figure 9-1)				
DOC fractionation (once initially)				
Flow		x(6)		
Conductivity		x(6)		
Temperature		x(6)		
pH		x(6)		
DOC		x(6)		
Surface water impoundments[a]				x[c]
Baseline water quality[b]			x	
Limited water quality		x[b]		
GROUNDWATER:				
Alluvial holes[a] (Figure 9-1)				
DOC fractionation (once initially at new holes)				
Water levels	x(3)	x(5)		
Limited water quality[d]		x(8)		
Baseline water quality[d]			x(8)	
Dual aquifer monitor holes (Figure 9-1)				
Water levels	x(6)			
Baseline water quality[d]				x(6)[e]

( ) Indicates the number of sampling sites.

[a] When water is present.

[b] These analyses will be performed downgradient of any surface water impoundments which are constructed.

[c] Additional measurements will be made if unexpected events occur.

[d] See Table 9-2 for listing of water quality constituents.

[e] To be conducted annually.

Note: Samples will be retained 30 days following submission of year-end report.

TABLE 9-2. WATER QUALITY SAMPLING, TRACT C-a

Constituents	Alluvial wells		Deep wells[b]	Seeps and springs	Stream gaging stations		Surface impoundments[c]	
	Q	S	A	Q	Q	S	Q	S
General water quality measures								
Specific conductance	X	X	X	X		X		X
Dissolved solids		X	X			X		X
Alkalinity	X	X	X	X	X	X	X	X
pH	X	X	X		X	X	X	X
Temperature	X	X	X	X		X		X
Fecal coliforms						X		X
Total coliforms						X		X
Color		X	X			X		X
Odor		X	X			X		X
Turbidity						X		X
Dissolved oxygen						X		X
Major inorganics								
Sulfate	X	X	X		X	X	X	X
Sulfide		X	X			X		X
Bicarbonate	X	X	X		X	X	X	X
Carbonate		X	X			X		X
Chloride	X	X	X		X	X	X	X
Fluoride	X	X	X		X	X	X	X

(continued)

TABLE 9-2. (continued)

Constituents	Alluvial wells		Deep wells[b]	Seeps and springs	Stream gaging stations		Surface impoundments[c]	
	Q	S	A	Q	Q	S	Q	S
Major inorganics (continued)								
Calcium	X	X	X		X	X	X	X
Magnesium	X	X	X		X	X	X	X
Potassium	X	X	X		X	X	X	X
Silica	X	X	X		X	X	X	X
Sodium	X	X	X		X	X	X	X
Ammonia		X	X			X		X
Nitrate+nitrite	X	X	X		X	X		X
Dissolved phosphate		X	X			X		X
Total phosphate						X		X
Orthophosphate						X		X
Organic constituents								
DOC		X	X	X	X	X	X	X
DOC fractionation						X[d]		X[d]
BOD						X		X
COD		X	X			X		X
Suspended organic carbon						X		X
Phenols		X	X			X		X
Oil and grease		X				X		X

(continued)

TABLE 9-2 (continued)

Constituents	Alluvial wells		Deep wells[b]	Seeps and springs	Stream gaging stations		Surface impoundments[c]	
	Q	S	A	Q	Q	S	Q	S
Organic constituents (continued)								
Kjeldahl nitrogen						X		X
MBAS						X		X
Cyanide		X	X			X		X
Pesticides						X		X
Trace elements								
Aluminum		X	X			X		X
Arsenic		X	X			X		X
Barium		X	X			X		X
Beryllium		X	X			X		X
Bismuth		X	X			X		X
Boron		X	X			X		X
Bromide		X	X			X		X
Cadmium		X	X			X		X
Chromium		X	X			X		X
Copper		X	X			X		X
Germanium		X	X			X		X
Gallium		X	X			X		X
Iron		X	X			X		X
Lead		X	X			X		X

(continued)

TABLE 9-2 (continued)

Constituents	Alluvial wells		Deep wells[b]	Seeps and springs	Stream gaging stations		Surface impoundments[c]	
	Q	S	A	Q	Q	S	Q	S
Trace elements (continued)								
Lithium		X	X			X		X
Mercury		X	X			X		X
Molybdenum		X	X			X		X
Manganese		X	X			X		X
Nickel		X	X			X		X
Selenium		X	X			X		X
Strontium		X	X			X		X
Titanium		X	X			X		X
Vanadium		X	X			X		X
Zirconium		X	X			X		X
Zinc		X	X			X		X
Radiological constituents								
Gross alpha[e]		X	X			X		X
Gross beta[f]		X	X			X		X

---

[a] Sampling frequency: Q = quarterly; S = semiannually; A = annually.

[b] Upper Aquifer.

[c] Sampled when water present.

[d] Once initially and repeated thereafter if DOC exceeds four times baseline mean.

[e] If gross alpha > 4 pCi/l, then Ra-226 and natural uranium added.

[f] If gross beta > 100 pCi/l, then Sr-90 and Ce-137 added.

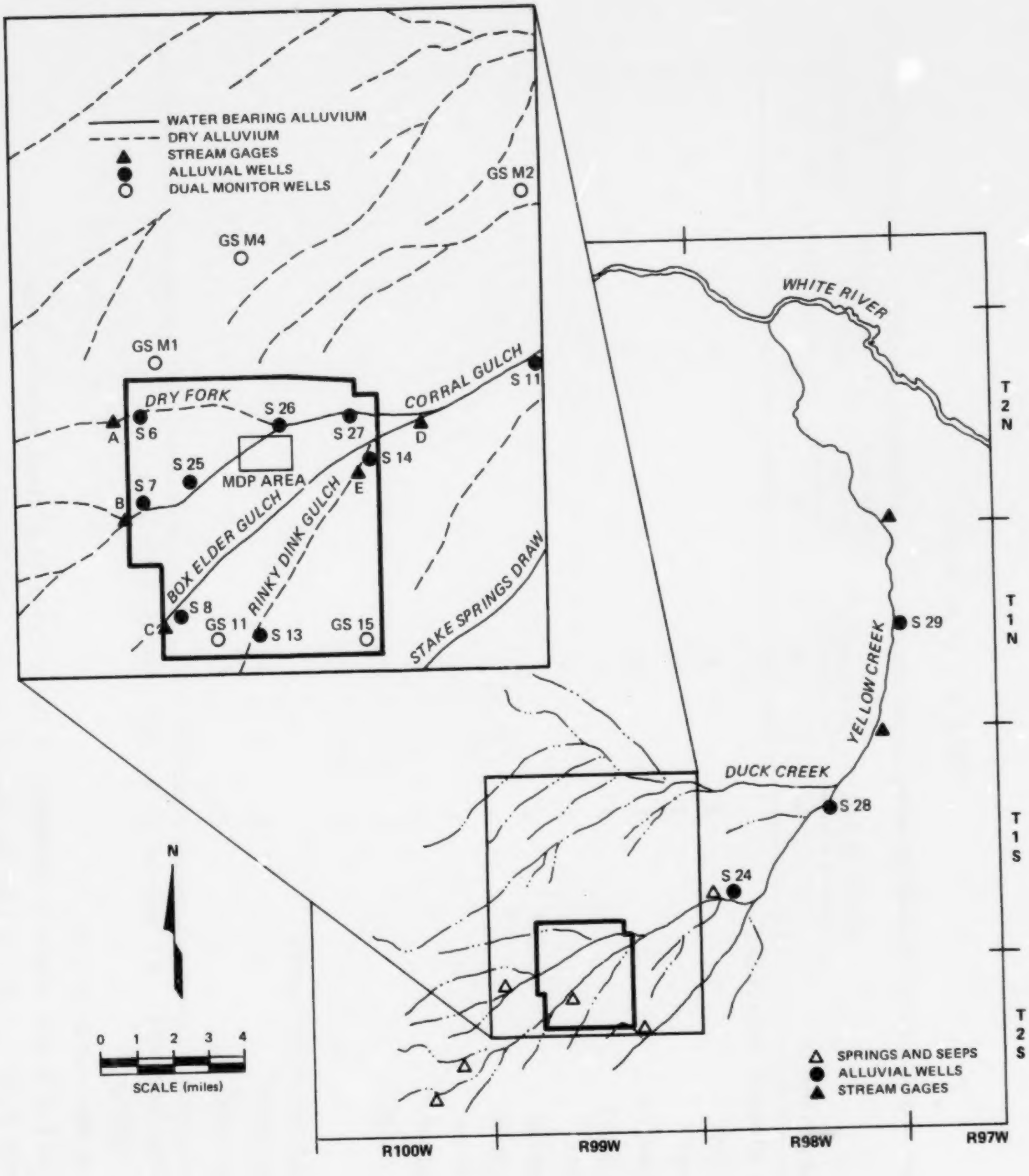

WATER BEARING ALLUVIUM
DRY ALLUVIUM
STREAM GAGES
ALLUVIAL WELLS
DUAL MONITOR WELLS
GS M2
GS M4
GS M1
DRY FORK
S 26
S 27
CORRAL GULCH
S 11
A
S 6
D
S 25
S 14
E
S 7
MDP AREA
B
BOX ELDER GULCH
RINKY DINK GULCH
STAKE SPRINGS DRAW
S 8
C
GS 11
S 13
GS 15
WHITE RIVER
T 2 N
T 1 N
S 29
YELLOW CREEK
DUCK CREEK
S 28
T 1 S
S 24
T 2 S
N
0 1 2 3 4
SCALE (miles)
SPRINGS AND SEEPS
ALLUVIAL WELLS
STREAM GAGES
R100W
R99W
R98W
R97W

Figure 9-1. Locations of MDP surface water and groundwater monitoring stations, Tract C-a.

- Identification of water quality perturbations will be based on conductivity and DOC monitoring
  - No change will be assumed to have occurred if conductiv- is less than 20 percent above baseline maximum or more than 20 percent below baseline minimum
  - DOC fractionation will follow observation of DOC greater than four times baseline mean concentration

- Surface gaging station program (Figure 9-1)
  - If unexpected flows are observed, additional samples will be collected (flow, conductivity, temperature, and pH) as needed to identify source
  - DOC fractionation will follow observation of DOC greater than four times baseline mean concentration
  - If conductivity at Station D (Figure 9-1), located at the confluence of watersheds draining the tract, exceeds the 1 percent frequency level (as defined for the baseline) for more than 3 consecutive days, samples will be analyzed for sodium, chloride, silica, calcium, magnesium, sulfate, potassium, bicarbonate, nitrate plus nitrite, pH, and DOC to assess origin of anomaly; the semiannual list of constituents may also be sampled
  - An automatic (predetermined periodicity) sampler will be installed at Station D; samples will be analyzed for oil and grease to detect accidental spills and leaks
  - Discriminant function analysis (using alkalinity, sodium, silica, fluoride, and pH) is used to classify source of waters (alluvium, Upper Aquifer, or Lower Aquifer); correlation studies will also be utilized
  - Data will also be compared to baseline data plotted on trilinear diagrams
  - Cation-anion balances will be used to check data.

Groundwater monitoring programs include sampling of alluvium, Upper Aquifer, and Lower Aquifer. Features of thse programs for the MDP are summarized as follows:

- Alluvial aquifers (Figure 9-1)
  - Increased concentrations of DOC or oil and grease will lead to additional analyses to determine type of material (e.g., No. 2 diesel fuel, gasoline, shale oil, etc.)

-- DOC fractionation will follow observation of DOC levels four times baseline mean concentration

-- Discriminant function analysis, correlation studies, and trilinear diagrams will be used as described above

- Deep aquifers (Figure 9-1): Water quality data will be compared to baseline study trilinear diagrams and correlation studies.

In addition to the above-described monitoring during the MDP, a program specifically oriented toward monitoring the MDP pump tests (Table 9-3) is described as follows:

- Three additional surface water stations
- Eight additional alluvial sites (11 total holes)
- Sixteen erosion and sedimentation sites.

For water quality monitoring, if pH varies 1.5 units from baseline values or conductivity varies ±20 percent for 3 consecutive days, then major plus minor constituents will be analyzed.

TRACT C-b MONITORING

Proposed monitoring of Tract C-b development also includes sampling of surface streams, springs and seeps, alluvial wells, and deep aquifer wells (Table 9-4). Features of the monitoring program are summarized as follows:

- Springs and seeps (Figure 9-2)

  -- If monthly sampled levels of pH, conductivity, dissolved oxygen, and temperature exceed baseline maximum or minimum levels by ±20 percent, additional water quality samples will be collected (the sampling frequency was changed to weekly in April 1979)

  -- Semiannual DOC fractionation will be at two springs selected by the AOSS Office

  -- Flow will be monitored on the following schedule:

Frequency*	Station
Quarterly	S-3, S-7
Semiannually	S-1, S-6
Annually	S-2, S-4, S-9, S-10

---

*(All stations are monitored weekly as of April 1979.)

TABLE 9-3. SUMMARY OF MDP AQUIFER TEST MONITORING PROGRAM, TRACT C-a

Program component	Monitoring sites	Summary of sampling
New surface water monitoring sites (Figure 9-1)	1. Corral Gulch at 84 Ranch 2. Sec. 1, T1S, R98W 3. Sec. 1, T1N, R98W	Flow measured with flume or weir with continuous recorder. Measure pH and conductivity: • Daily for 3 days prior to pump test discharge • Twice daily for initial week of discharge • Twice per month thereafter.
New alluvial wells (Figure 9-1)	1. G-S S-27 Triple 2. G-S S-11 Triple 3. G-S S-11A Dual 4. G-S S-24 Single 5. G-S S-28 Dual 6. G-S S-28A Dual 7. G-S S-29 Dual 8. G-S S-29A Dual	Measure water level, conductivity, temperature, and pH daily for 3 days prior to pump test discharge. Measure major or minor chemical constituents in wells with water or as water is encountered: • Once daily for initial 2-3 days of discharge • Once weekly thereafter
Deep aquifer wells (Figure 9-1)	1. Upper: G-S 11 G-S 15 G-S M1 G-S M2 G-S M3 G-S M4 2. Lower: G-S 15	Measure water level once daily for 2-3 days after pumping started to established trend, then weekly
Erosion and sedimentation monitoring sites	Sixteen sites distributed along Corral Gulch and Yellow Creek, on and below Tract C-a	Measure channel cross sections. Photograph sites.

TABLE 9-4. WATER QUALITY SAMPLING PROGRAM--TRACT C-b

	Alluvial wells[b]		Deep aquifers		Seeps and springs				Stream gaging stations			
	M	Q	S	A	M	Q or S	S	A	M or Q	Q	S	A
General water quality measures												
Specific conductance	X				X				X			
Dissolved solids		X	X			X			X			
Alkalinity		X	X			X			X			
pH	X	X	X		X	X			X			
Temperature	X	X	X		X	X			X			
Fecal coliforms		X					X					
Total coliforms		X					X					
Dissolved oxygen	X				X							
Hardness		X			X			X				
Major organics												
Sulfate		X	X			X			X			
Sulfide										X		
Bicarbonate		X	X			X			X			
Carbonate		X	X			X			X			
Chloride		X	X						X			
Fluoride		X	X			X			X			
Calcium		X	X			X			X			
Magnesium		X	X			X			X			
Potassium		X	X			X			X			
Silica									X			
Sodium		X	X			X			X			
Ammonia		X	X			X			X			

(continued)

TABLE 9-4 (continued)

	Alluvial wells[b]		Deep aquifers		Seeps and springs				Stream gaging stations			
	M	Q	S	A	M	Q or S	S	A	M or Q	Q	S	A
Organic constituents												
Nitrate		X	X			X						
Nitrate + nitrite									X			
Total phosphate									X			
DOC			X						X			
DOC fractionation		X					X				X	
BOD		X	X			X				X		
COD		X	X			X				X		
Suspended organic carbon									X			
Phenols		X	X			X				X		
Oil and grease		X	X			X						
Kjeldahl nitrogen		X	X			X			X			
MBAS		X									X	
Cyanide										X		
PNA				y								
Trace elements												
Aluminum		X	X			X				X		
Arsenic		X	X			X			X			
Barium		X	X			X				X		
Boron		X	X			X			X			
Bromide		X	X				X			X		
Cadmium		X				X				X		
Chromium		X	X			X				X		
Cobalt			X									

(continued)

TABLE 9-4 (continued)

	Alluvial wells[b]		Deep aquifers		Seeps and springs				Stream gaging stations			
	M	Q	S	A	M	Q or S	S	A	M or Q	Q	S	A
Trace elements (continued)												
Copper		X	X			X				X		
Iron		X	X			X			X			
Lead		X	X			X				X		
Lithium		X	X							X		
Mercury		X	X							X		
Molybdenum		X	X			X				X		
Manganese		X	X			X			X			
Nickel		X	X			X						
Selenium		X	X			X				X		
Silver		X	X			X						
Strontium		X	X			X						
Zinc		X	X			X				X		
Complete element scan										X		
Radiological constituents												
Gross alpha		X	X				X			X		
Gross beta		X	X				X			X		
Sediments												
Suspended sediment									X			
Sediment pesticide											X	
Sediment characterization												X

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[a] Sampling frequency: M = monthly; Q = quarterly; S = semiannually; A = annually.

[b] Water quality sampling of alluvial wells has been changed to a quarterly frequency.

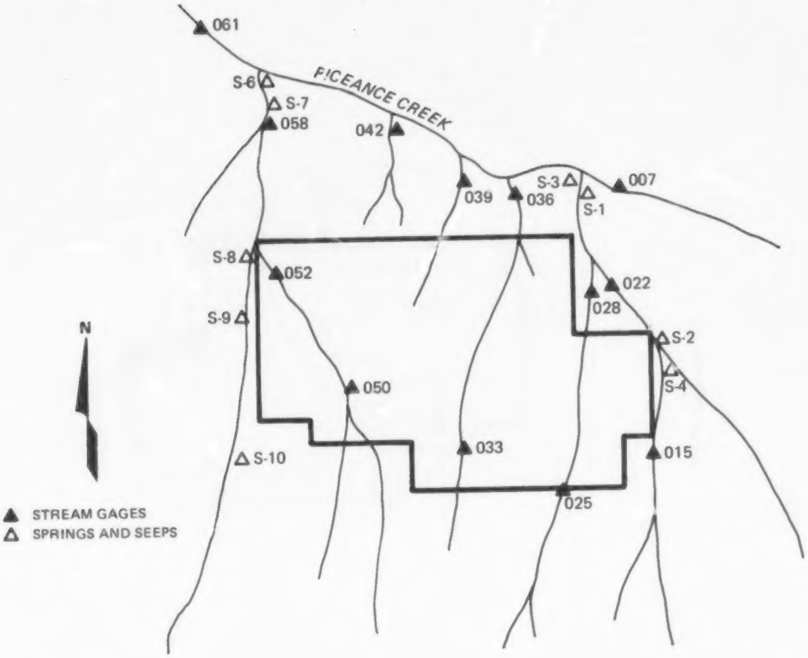
PICEANCE CREEK
061
S-6
S-7
058
042
039
036
S-3
S-1
007
S-8
052
S-9
022
028
S-2
S-4
050
033
015
S-10
025
N
▲ STREAM GAGES
△ SPRINGS AND SEEPS

Figure 9-2. Surface water monitoring stations, Tract C-b.

- Surface gaging stations (Figure 9-2)
  - -- Monthly and quarterly sampling programs are conducted at four major stations: 007, 022, 058, 061
  - -- Additional quarterly sampling will be conducted at ephemeral stream stations on an opportunistic basis (when flow is present)
- Alluvial wells (Figure 9-3): In addition to the program shown in Table 9-4 and Figure 9-3, wells A-2, A-3, A-5, A-6, and A-7 will be monitored on a "reduced basis" when A-2A, A-3A, A-5A, A-6A, and A-7A are completed
- Upper Aquifer wells (Figure 9-3): Polynuclear aromatics (PNA) will be sampled annually at "selected" locations and species analyzed will be determined "at a later date."

The Tract C-b monitoring plan designates the following chemical constituents as "indicator variables:"

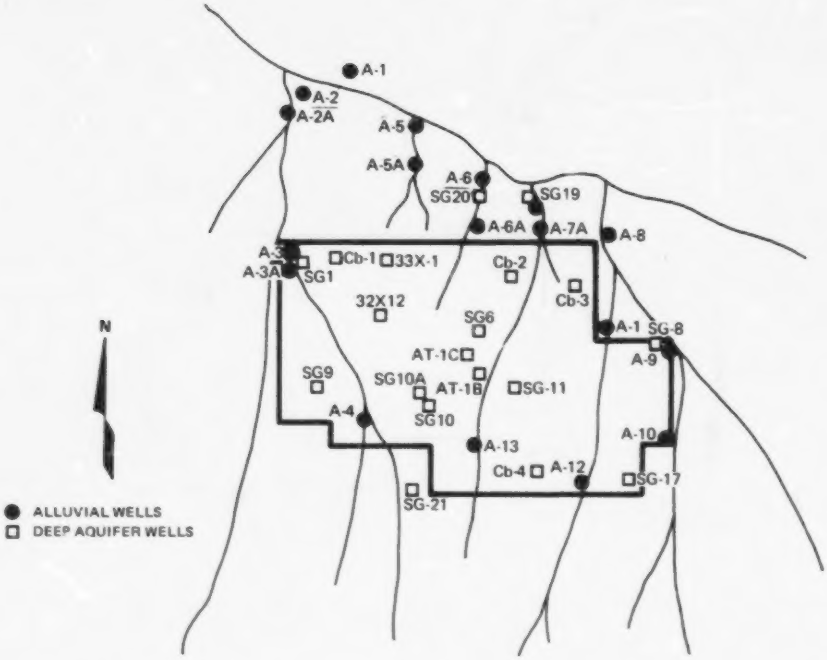
A-1
A-2
A-2A
A-5
A-5A
A-6
SG20
SG19
A-6A
A-7A
A-8
A-3
A-3A
SG1
Cb-1
33X-1
Cb-2
Cb-3
32X12
SG6
A-1
SG-8
A-9
N
AT-1C
SG9
SG10A
AT-1B
SG-11
A-4
SG10
A-10
A-13
Cb-4
A-12
SG-17
SG-21
ALLUVIAL WELLS
DEEP AQUIFER WELLS

Figure 9-3. Alluvial and deep aquifer monitoring wells, Tract C-b.

Indicator variable	Springs	Gaging stations	Alluvium	Upper Aquifer
General water quality measures:				
Conductivity			X	
Coliform bacteria	X		X	
pH	X	X	X	X
Temperature		X	X	X
TDS	X	X	X	X
Inorganic chemical constituents:				
Ammonia	X	X		
Arsenic	X	X	X	X
Boron	X	X	X	X
Fluoride	X	X	X	X
Mercury		X		
Selenium		X		
Organic chemical constituents:				
DOC				X
MBAS		X		
Oil and grease		X	X	X
Phenolics	X			

Tract C-b monitoring plan "indicator variables" (continued)

Indicator variable	Springs	Gaging stations	Alluvium	Upper Aquifer
Radiological water quality (Table 9-4)				X
Groundwater level			X	X
Sediment		X		
Streamflow		X		
Precipitation		X		

OTHER MONITORING PROGRAMS

Monitoring and testing programs conducted by organizations other than the tract developers may also be useful for monitoring the impact of tract development on groundwater quality. One example is the program of surface water and groundwater sampling conducted by the U.S. Geological Survey in the Piceance Basin (Welder and Saulnier, 1974; Weeks and Welder, 1974; Ficke, Weeks, and Welder, 1974). Many of these programs are regional in focus but, although they offer data useful for characterizing the hydrgeology and water quality of development tract areas, they probably do not provide sampling sites suitable for site- and source-specific monitoring programs.

GENERAL MONITORING APPROACH

Baseline studies conducted on Tracts C-a and C-b can be generally described as regionally focused programs. Proposed monitoring programs (considering deep aquifers which are the emphasis of this study) are also largely regional in orientation. Consider, for example, Tract C-a development. Figure 9-4 shows monitoring plans for the MDP operation. Five deep (dual completion) wells are located approximately 2 miles or more from the MDP area, two generally to the south (G-S 11 and G-S 15) and three generally to the north (G-S M1, G-S M4, and G-S M2). Figure 9-4 shows an anisotropic flow net for the Upper Aquifer superimposed on the plot plan for Tract C-a. Comparison of these flow net data with the deep well locations identified on Figure 9-1 indicates that no upgradient-downgradient (relative to the MDP area) pairs of wells are included in the MDP monitoring plan. G-S 11 and G-S M1 may provide general background water quality data, but none of the other wells are shown to be directly downgradient. Figure 9-4 indicates that CE 709 and G-S 9 may provide existing well upgradient monitoring sites for the MDP and G-S 4-5, TO 3, and CE 702 may be better existing downgradient sites for monitoring MDP operations. Even so, these downgradient wells are located about ½ mile (G-S 4-5) to 1 mile (TO 3 and CE 702) from the MDP area. A better option may be a new well or wells located at the downgradient edge of the MDP retort field. Another alternative which needs further assessment is the utility of wells included in the dewatering-reinjection program for monitoring after cessation of dewatering.

A similar situation exists for Tract C-b monitoring as illustrated in Figure 9-5. Several wells (32X-12, 33X-1, and Cb-1) are located in the immediate

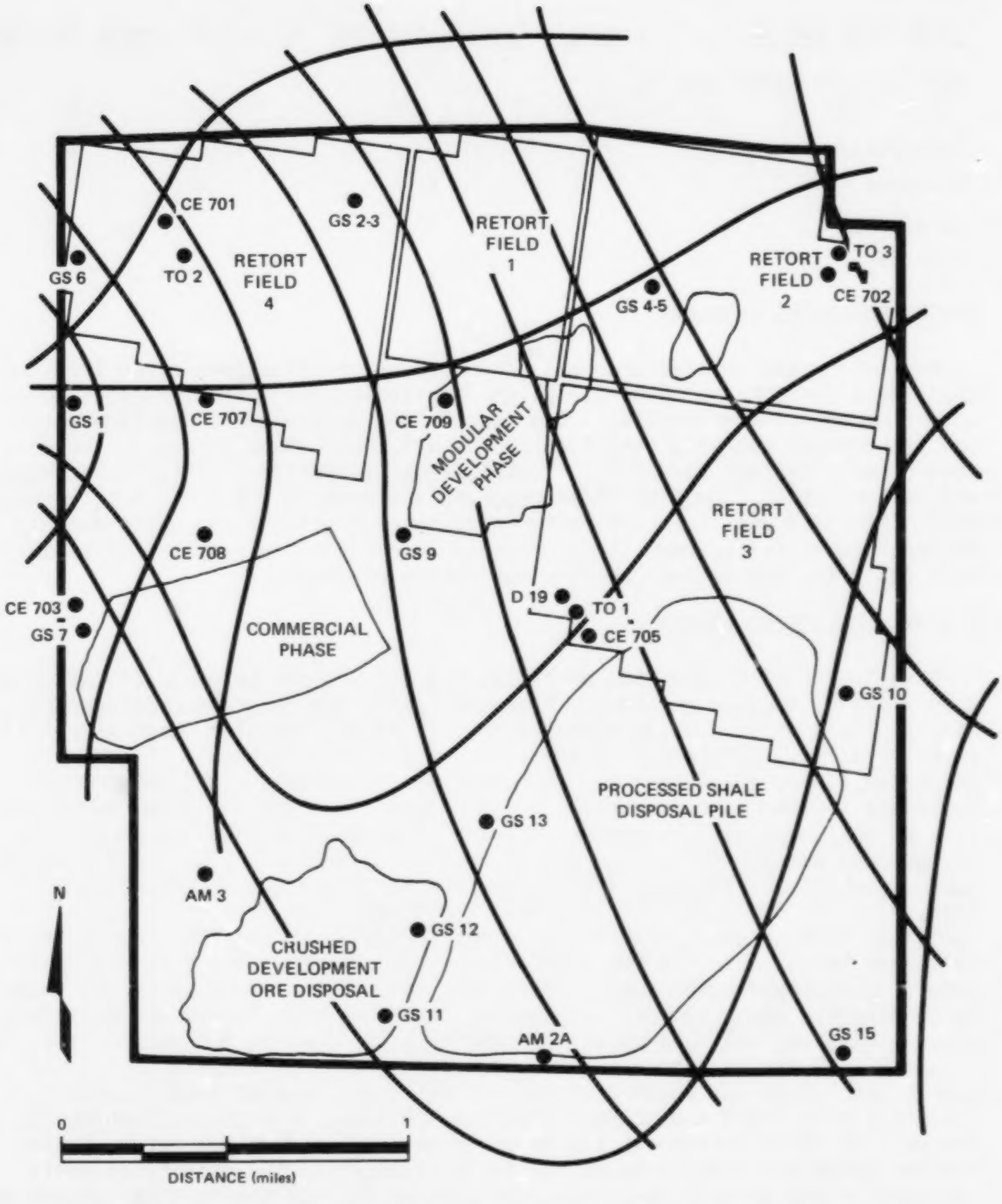
CE 701
GS 2-3
RETORT FIELD 1
GS 6
TO 2
RETORT FIELD 4
RETORT FIELD 2
TO 3
CE 702
GS 4-5
GS 1
CE 707
CE 709
MODULAR DEVELOPMENT PHASE
RETORT FIELD 3
CE 708
GS 9
D 19
TO 1
CE 703
GS 7
COMMERCIAL PHASE
CE 705
GS 10
PROCESSED SHALE DISPOSAL PILE
GS 13
N
AM 3
GS 12
CRUSHED DEVELOPMENT ORE DISPOSAL
GS 11
AM 2A
GS 15
0
1
DISTANCE (miles)

Figure 9-4. Anisotropic flow net of Upper Aquifer superimposed on Tract C-a plot plan and existing deep aquifer wells.

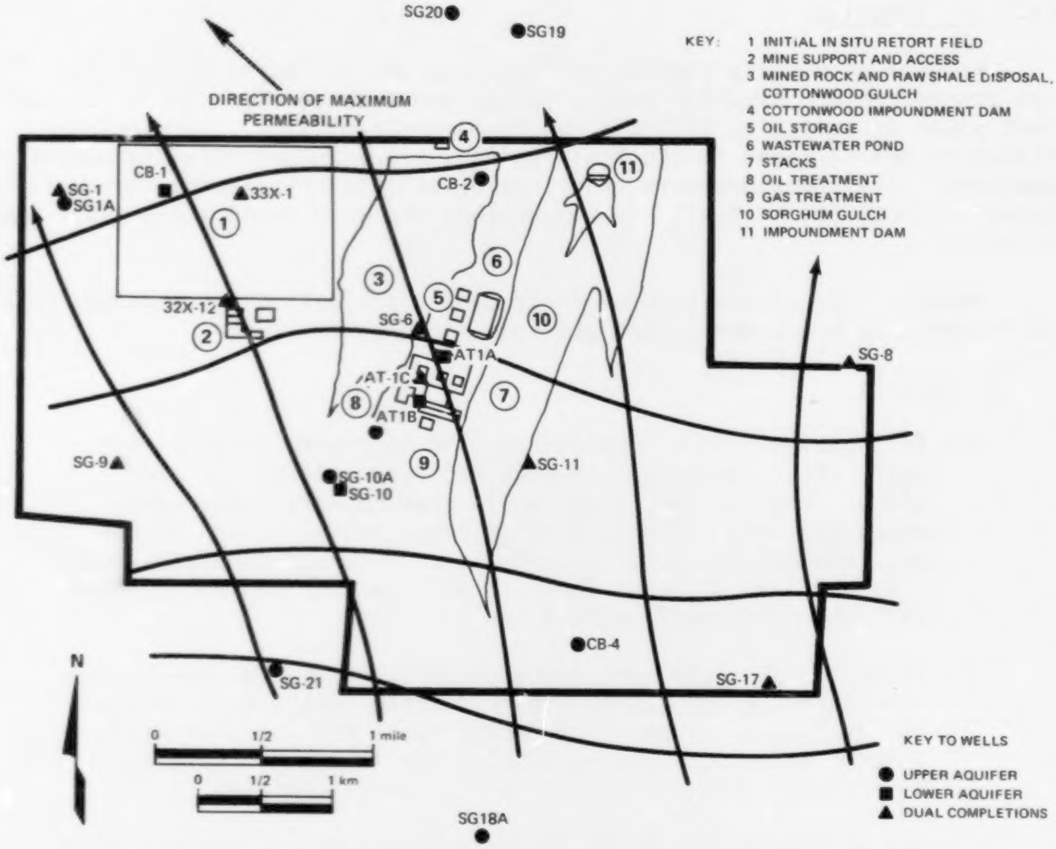
SG20
SG19
DIRECTION OF MAXIMUM PERMEABILITY
KEY:
1 INITIAL IN SITU RETORT FIELD
2 MINE SUPPORT AND ACCESS
3 MINED ROCK AND RAW SHALE DISPOSAL, COTTONWOOD GULCH
4 COTTONWOOD IMPOUNDMENT DAM
5 OIL STORAGE
6 WASTEWATER POND
7 STACKS
8 OIL TREATMENT
9 GAS TREATMENT
10 SORGHUM GULCH
11 IMPOUNDMENT DAM
SG-1
SG1A
CB-1
33X-1
CB-2
32X-12
SG-6
AT1A
AT-1C
AT1B
SG-8
SG-9
SG-10A
SG-10
SG-11
CB-4
SG-21
SG-17
N
0
1/2
1 mile
0
1/2
1 km
SG18A
KEY TO WELLS
● UPPER AQUIFER
■ LOWER AQUIFER
▲ DUAL COMPLETIONS

Figure 9-5. Anisotropic flow net of Upper Aquifer superimposed on Tract C-b development plot plan.

vicinity of (or within) the proposed retort field. Wells 32X-12 and 33X-1 are Upper Aquifer wells; they are open holes with packers set at the top of the Mahogany Zone. They will be impacted by mining. Well Cb-1 is perforated in the Lower Aquifer zone. No wells are located downgradient of the retort field area. Until recently, the Uinta Aquifer (U_1) was not monitored in or near the retort field. The new wells were completed in the Uinta downgradient of the retort field.

Monitoring of dewatering-reinjection wells may be better focused on the wells themselves except for hydrogeologic modifications (e.g., head levels).

SAMPLING METHODS

In order to better evaluate existing or proposed monitoring programs, as well as the existing data base, sampling methods being utilized on Tracts C-a and C-b were reviewed in available documents and by direct observation.

Tract C-a Sampling

Groundwater quality samples on Tract C-a are collected by bailing. Similar procedures are used for both alluvial and deep aquifer sampling. Sufficient water is bailed to fill the required sample bottles. Samples requiring filtration are filtered in the field using a nitrogen-positive pressure filter apparatus. Field measurements of pH (using colorimetric paper), conductivity (using conductivity bridge), and temperature are made immediately after sample collection.

Comments from observation of field sample collection (in December 1978) and response by tract developers are summarized as follows:

- Comments

  1. Alluvial wells are constructed with approximately a 6-inch outer steel casing and <3-inch PVC inner casing for sampling. When bailed, these wells produce very muddy water which probably reflects fine sediment in the bottom of the well and not the local groundwater. More representative samples would be obtained from a gravel-packed, fully developed well and from a well pumped for sampling.

  2. To obtain a sample more representative of groundwaters rather than waters which may have been sitting in the well casing for some time, it would be necessary to bail several well volumes before collecting samples for analysis. At present, only enough water is bailed to fill sample bottles.

  3. How well to field pH measurements made with colorimetric tape compare with laboratory pH data? As turbidity is a severe problem in some of the wells, it would be better to filter the samples and then test for pH (and also electrical conductivity). In addition, a watertight case with desiccant material for storage of indicator tape may be useful for assuring the consistency of pH tape data.

  4. Field personnel indicated that 3 to 4 days delay is common prior to delivery of samples to the analytical laboratory. Has any work been done to look at the effects of this delay time on analytical results?

  5. Construction of the deep wells is similar to shallow wells, except that perforated zones are about 300 feet thick and piezometric levels stand 100 to 200 feet above the perforations. Sampling of these wells was not observed in December 1978; however, it was reported that these wells are not pumped before sampling and that these wells commonly contain dirty or muddy water. As noted above, this probably is not representative of local groundwater. A 6-inch casing, 300 feet long, contains about 450 gallons of water. Approximately 4 gallons are bailed in a single sampling. Thus, the relation

between the water sampled (which may have been in the well for some time) and the local groundwater may be questionable.

6. Steel casing may affect trace metal and organic chemical analyses, as these constituents may be absorbed by metal oxides on the casing.

7. A monthly sampling frequency for many of the alluvial wells seems excessive, particularly those which contain little or no water. These monitoring efforts are related to detection of leakage from the reinjection program. However, with the present operation of the reinjection system and the continuing dry state of many of the wells, some adjustment may be justified for the future.

- Response from Rio Blanco Oil Shale Company

1. The statement made is generally correct with the following exception: the alluvial monitor holes are gravel-packed and have been developed. The nature of the alluvial aquifers is such that coarser material has been deposited with very fine clay-like material as water is withdrawn from the wells. This fine, clay-like material is also produced from the well. It is our opinion that the majority of the sediment produced in the sample is from the aquifer. If sediment-free wells were to be constructed, the cost would be quite high in that a very fine, wire-wound screen would have to be used with a carefully selected gravel pack. Even if these precautions were taken, it is still not 100 percent certain that sediment-free water could be produced.

2. In some of the alluvial holes, it is possible to remove a few volumes of water before collecting the sample for analysis. However, in most of the holes, the transmissivity of the aquifer is such that after removing a few well volumes, the well would be dry and would require several days recovery before enough water would be in the well to obtain a sample.

3. A comparison of field pH data collected with a colorimetric tape cannot readily be compared with laboratory pH data since pH is not stable.

4. The field, as we all know, is quite remote from any analytical laboratory. We have been quite conscious of the delay resulting from getting the samples collected and to the laboratory for analysis. This delay, however, is kept to a minimum. At the present time, we have not conducted any work to compare the effects of this delay on the analysis.

5. The statement is correct in that we do not pump the wells before sampling. We do, however, collect the sample in the aquifer zone where water should be moving through the well.

We have made comparisons of the samples produced from the monitoring program with those produced from pumping tests. The results of these comparisons are quite favorable in that we find the analysis resulting from the two methods of collecting water very similar.

6. The use of steel casing is quite common in the completion of the observation holes. At the time the holes were completed, there was no other material economically available other than steel.

7. We agree.

Tract C-b Sampling

Two methods of sample collection are used for groundwater quality monitoring on Tract C-b. Pumping is used to sample alluvial wells and swabbing is used to sample deep aquifers. In sampling deep aquifers, several swabbing-discharge runs are made before samples for laboratory analysis are collected. Field measurements of pH and conductivity using field instruments are made at the time of sampling.

Comments and recommendations from observation of field collection operations (in November 1978) are summarized as follows:

- Bedrock aquifer sampling
  - -- Comments
    1. The diameter of the piezometers in use (2-3/8 inches) is too small for installation of a submersible pump for sampling. Use of pumping to obtain samples allows sampling a larger volume of the aquifer and provides more representative samples for analysis.
    2. The swabbing method being used may accelerate plugging of piezometer perforations. The small diameter of the piezometers also increases the likelihood of the plugging. Plugging may have resulted in retrieval of only a small volume of water from the well observed in November 1978; the third or fourth swabbing pass yielded little or no water. Pumping for sampling would help keep wells developed.
    3. Grease and oil were observed on the cable and other swabbing equipment. Since swabbing equipment is also used for oil well work, the potential exists for contamination of samples by sampling equipment.
    4. Steel piezometers may affect trace metal and organic chemical analyses. These constituents may be adsorbed on metal oxides on the casing.

-- Recommendations

1. The volume of water swabbed should be measured as should the number of swabbing passes in each piezometer. Such data would be useful for subsequent sampling surveys and also for evaluating plugging of wells.

2. The conductivity meter used in the field should either have a temperature compensator or water temperature should be measured along with conductivity at the time of sampling. Without this procedure, field data from one survey to the next cannot be compared; also, lab and field data cannot be compared.

3. Manufacturers' instructions and maintenance information for field instruments should be carried with field instruments, along with other sampling procedure instructions for the field team.

4. Since conductivity is being used to determine when it is appropriate to collect samples for chemical analysis, data from previous surveys should be available in the field for reference.

5. Sample filtration and preservation (including addition of chemical preservatives and icing of samples) should take place as soon as possible after collection, preferably in the field immediately after sample collection.

6. The depth of each swabbing run should be recorded.

7. For the recompletion program, PVC should be used in place of steel casing wherever possible.

8. Wherever possible [i.e., where adequately sized (>4-inch) casing is available], samples should be obtained by pumping.

9. Cable and swabbing cups previously used in oil field operations should be cleaned thoroughly before use in water quality sampling. Ideally, they should also be cleaned after each sampling to avoid contamination from one monitor well to another. However, a sufficient number of swabbing passes in each piezometer may minimize this latter source of contamination.

- Alluvial aquifer sampling

-- Comments

Sampling of alluvial wells was not observed during the November tour. Alluvial wells are equipped with a

4-inch-diameter PVC casing and are sampled by pumping.

-- Recommendations

1. Initial testing of each well with frequent sampling of discharge conductivity can be used to identify appropriate pumping time before sampling.

2. Eight-inch or larger wells would be required for any pump testing of the alluvial aquifer.

3. If pumping is used, it is not necessary to complete piezometers at various depths in the alluvium. Pumping would sample the aquifer profile in composite.

It should be noted that many of these recommendations were implemented by Tract C-b developers during 1979.

OTHER SAMPLING CONSIDERATIONS

Selection of Sampling Method

Previous discussion in this report has indicated that well completion and sampling methods can play an important part in determining the utility of monitoring data. During baseline studies on the oil shale tracts, several methods have been used to collect water quality samples: bailing, swabbing, and pumping. Each of these methods may sample a different part of the aquifer-well system and can result in different data for the same point in time and space.

Alluvial wells on Tract C-b have been sampled by both bailing and by pumping (C-b Shale Oil Venture, 1977b). Relatively high fluoride levels (5 mg/l) were reported for the initial sampling run when samples were collected by bailing. Subsequent samples for the 2-year baseline studies were collected by pumping and observed fluoride levels were lower and relatively constant (mean = 0.65 mg/l with standard error of mean = 0.09). The differences seem to be related to sampling method.

On Tract C-a, all groundwater quality samples are collected by bailing. Sufficient water is bailed to fill the required sample bottles. One of the goals of sampling is to obtain water quality data which are representative of water within the aquifer zone being sampled. Aside from problems of well completion, bailing of a small volume from a well bore may not provide the desired representative sample. As noted above, construction of deep wells may include a perforated zone of perhaps 300 feet. A 6-inch casing, 300 feet long, contains about 450 gallons of water. If approximately 4 gallons are bailed for sampling on, for example, a quarterly basis, water sampled may not be representative of local groundwater, but rather of the water which has been standing in the well bore (perhaps a very different physiochemical environment) for some time.

The implication here is that care must be taken with the use of bailing as a sampling technique. For example, tests conducted by Rio Blanco Oil Shale Project (Tract C-a) indicated that samples bailed from well intervals perforated in aquifer zones produced results very comparable to pumped water samples. However, samples bailed from the well interval above the perforated zone (and where water is stagnant within the well) yielded water quality data quite different from either pumped samples or samples bailed from the aquifer zone.

When swabbing is used to collect samples, there are several factors which influence the amount of water produced and also possibly the level of water quality constituents observed:

- Length of perforated interval swabbed
- Type of perforation
- Space between well and aquifer material; and between swabbing cup and well casing
- Depth to water
- Height of water column swabbed
- Speed of swabbing.

During swabbing runs on Tract C-b, conductivity measurements of each swabbing run are made as one criterion for determining when to collect samples for analysis. Wide ranges of conductivity may be observed during a given sampling effort (Table 9-5). Conductivity of initial swab runs may be higher or lower than the final value. The selection of when samples are collected (i.e., after what number of swab runs) can be seen to significantly affect the results of water quality sampling.

Pumping to collect water quality samples may produce representative aquifer samples, but pumping time and well completion play an important role in determining the results of sampling. For example, dissolved solids levels in pump test discharges (at well AT-1 on Tract C-b) were lower than levels observed in samples collected by swabbing. One explanation is that relatively good water quality zones are also zones of relatively high hydraulic conductivity. Pumping of wells completed in both such good water quality zones and poorer water zones would draw relatively more water from the good water quality zone, producing relatively low dissolved solids levels (C-b Shale Oil Venture, 1977b). If continued pumping can exhaust water in the good water quality zone, water quality can decline with continued pumping (Table 9-6).

Well Completion

As previously discussed (see Sections 5 and 6), well completion has a significant influence on hydrogeologic and water quality data. For example, consider the following data related to well recompletions on Tract C-b:

TABLE 9-5. CONDUCTIVITY LEVEL OF SWABBED SAMPLES, TRACT C-b, FALL 1976 (C-b Shale Oil Venture, 1977b).

Well/string number	Gallons swabbed	Observed conductivity range (μmhos/cm)	Final conductivity (μmhos/cm)
SG-1-1	1,260	3,000 - 10,000	8,250
SG-1-2	2,840	1,200 - 1,500	1,250
SG-9-1	2,100	1,300 - 3,400	2,000
SG-9-2	1,150	1,850 - 2,100	1,850
SG-21	3,210	750 - 1,150	1,000
Cb-4	2,300	800 - 900	825
SG-11-12	1,220	14,000 - 32,000	22,000
SG-11-2	530	800 - 4,000	1,200
SG-11-3	300	1,600 - 1,800	1,790
SG-18A	---	750 - 1,250	1,000
Cb-2	2,920	1,600 - 1,650	1,600
SG-6-1	550	1,800 - 3,100	3,000
SG-6-2	630	1,300 - 1,400	1,300
SG-6-3	160	1,350 - 1,550	1,550

TABLE 9-6. FLUORIDE AND BORON FROM LOWER AQUIFER TEST (C-b Shale Oil Venture, 1977b)

Date (1975)	Fluoride (mg/l)	Boron (mg/l)
January 20	18.0	0.65
February 5	18.1	0.88
February 23	20.0	1.15
February 24	20.1	1.10
February 25	20.4	1.13
February 27	18.4	1.2
February 28	20.4	1.6
March 1	20.2	1.42
March 3	19.0	2.58
March 5	20.0	2.02
March 7	21.2	2.18
March 19	23.2	2.00

Original well	TDS (mg/l) in water before recompletion	TDS (mg/l) in water after recompletion	New well designation
SG-11-1	39,000	16,000	SG-11-1R
SG-10	42,000	2,800	SG-10R
SG-17-1	28,000	4,300	SG-17-1R

These wells had initially encountered, and had been open to, an interval containing highly saline water which appeared to have a higher hydrostatic head than the overlying aquifer intervals. Thus, water collected from these overlying layers was affected by the interconnection. Recompletions were undertaken to isolate these different water quality bodies.

Thus, with initial data collection and the resultant gain in knowledge about the hydrogeologic system, modifications in well construction may be needed. An extensive recompletion program is proposed for Tract C-b to address the present concept of a stratified aquifer system.

Analysis of the hydrologic testing which has been completed on Tract C-b to date indicates that the simplified concept of an "Upper Aquifer" is, in reality, a more complex system comprised of highly stratified layers of different permeability. In the initial mine plans, waters of the Upper Aquifer are projected to remain segregated from other waters of the Lower Aquifer. During the first phase of shaft sinking, very little, if any, stress will be put on the Upper Aquifer. However, major stress will be applied on the Upper Aquifer by lateral drifting and subsequent dewatering as the mine expands. As this phase of development progresses, the Upper Aquifer will be monitored with present drill holes on and off Tract C-b. According to initial plans of developers, additional completion of existing holes, and perhaps additional holes, were to be made to isolate the "Uinta Aquifer" from the other Upper Aquifer subunits (Figure 9-6). However, data provided in Figures 9-7 and 9-8, and Tables 9-7 and 9-8, do not clearly indicate this fact. The Uinta Aquifer is highly protective and permeable only in the northwest part of Tract C-b (in the vicinity of the in-situ retort field). It is predicted, with the present scheme for dewatering, that effects above the Four Senators Zone will be minimal since the Four Senators Zone acts as an aquitard or possibly an aquiclude, prohibiting vertical movement of water within the Upper Aquifer zone. Fracturing of the Four Senators Zone during mine and retort development may alter this situation. Later analysis by developers led to the inclusion of the Uinta Aquifer in UPC_1.

The proposed Tract C-b monitoring program uses the present wells on and off tract. In general, modifications will be made in the shallow tubing strings so that the sections above and below the Four Senators Zone can be monitored separately. New wells 33X-1 and 32X-12 are included in the monitoring program (Figure 9-6), although they are expected to be impacted by mining and hence may be of limited use. Figure 9-4 shows the present completions of deep wells on tract. Figure 9-7 contains the planned recompletions

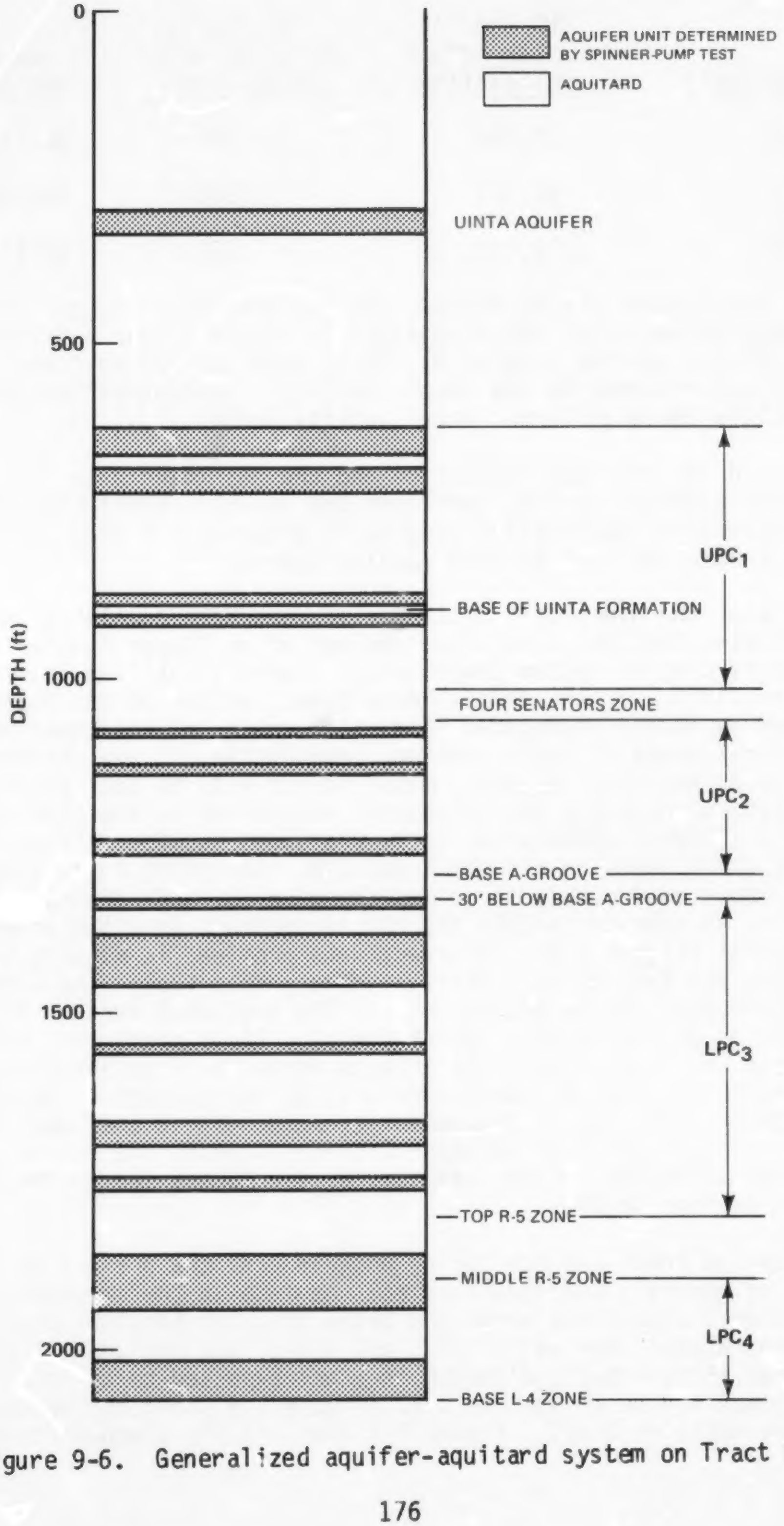
0
500
1000
1500
2000
DEPTH (ft)
AQUIFER UNIT DETERMINED BY SPINNER-PUMP TEST
AQUITARD
UINTA AQUIFER
UPC$_1$
BASE OF UINTA FORMATION
FOUR SENATORS ZONE
UPC$_2$
BASE A-GROOVE
30' BELOW BASE A-GROOVE
LPC$_3$
TOP R-5 ZONE
MIDDLE R-5 ZONE
LPC$_4$
BASE L-4 ZONE

Figure 9-6. Generalized aquifer-aquitard system on Tract C-b.

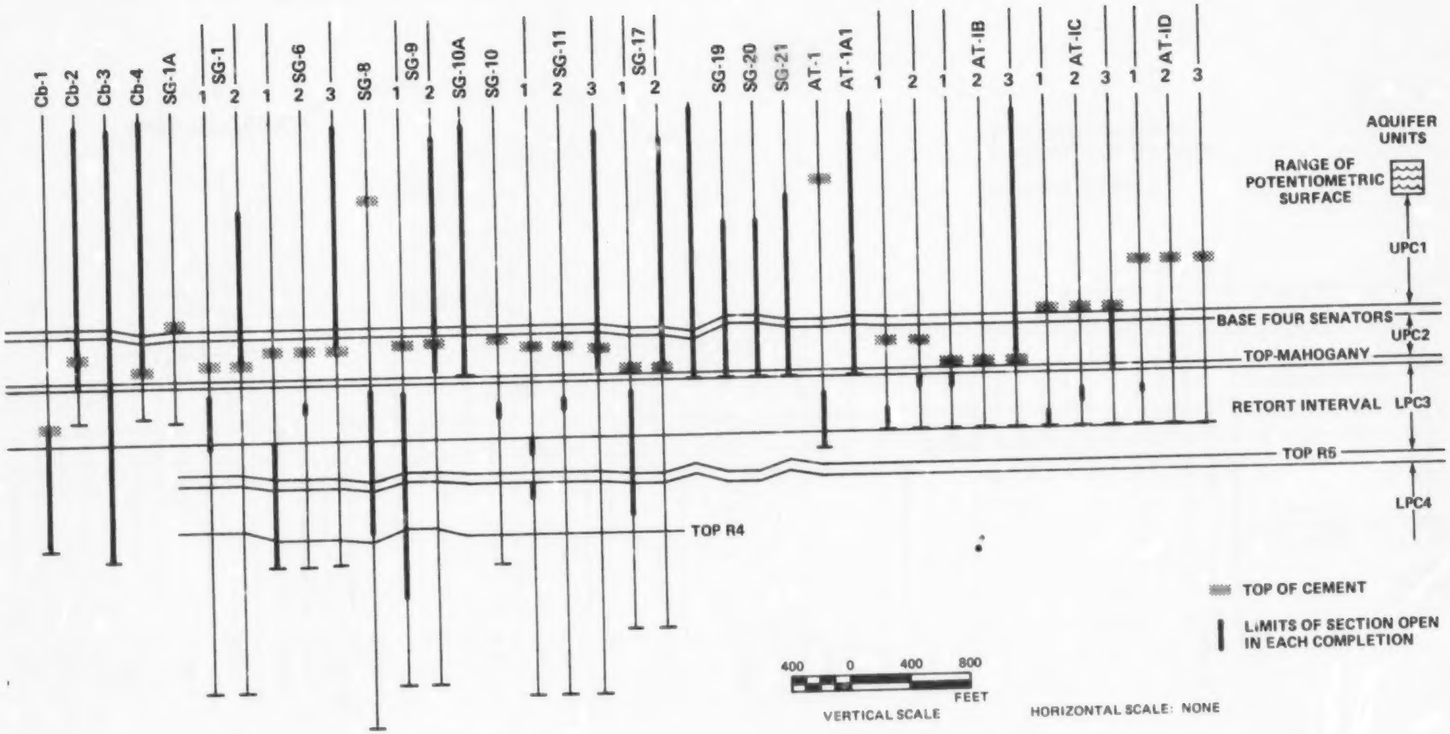
Cb-1
Cb-2
Cb-3
Cb-4
SG-1A
SG-1 1 2
SG-6 1 2 3
SG-8
SG-9 1 2
SG-10A
SG-10
SG-11 1 2 3
SG-17 1 2
SG-19
SG-20
SG-21
AT-1
AT-1A1
1
2
AT-IB 1 2 3
AT-IC 1 2 3
AT-ID 1 2 3
AQUIFER UNITS
RANGE OF POTENTIOMETRIC SURFACE
UPC1
BASE FOUR SENATORS
UPC2
TOP-MAHOGANY
RETORT INTERVAL
LPC3
TOP R5
LPC4
TOP R4
TOP OF CEMENT
LIMITS OF SECTION OPEN IN EACH COMPLETION
400 0 400 800
FEET
VERTICAL SCALE
HORIZONTAL SCALE: NONE

Figure 9-7. Current well completions, subsurface hydrology monitoring program, Tract C-b.

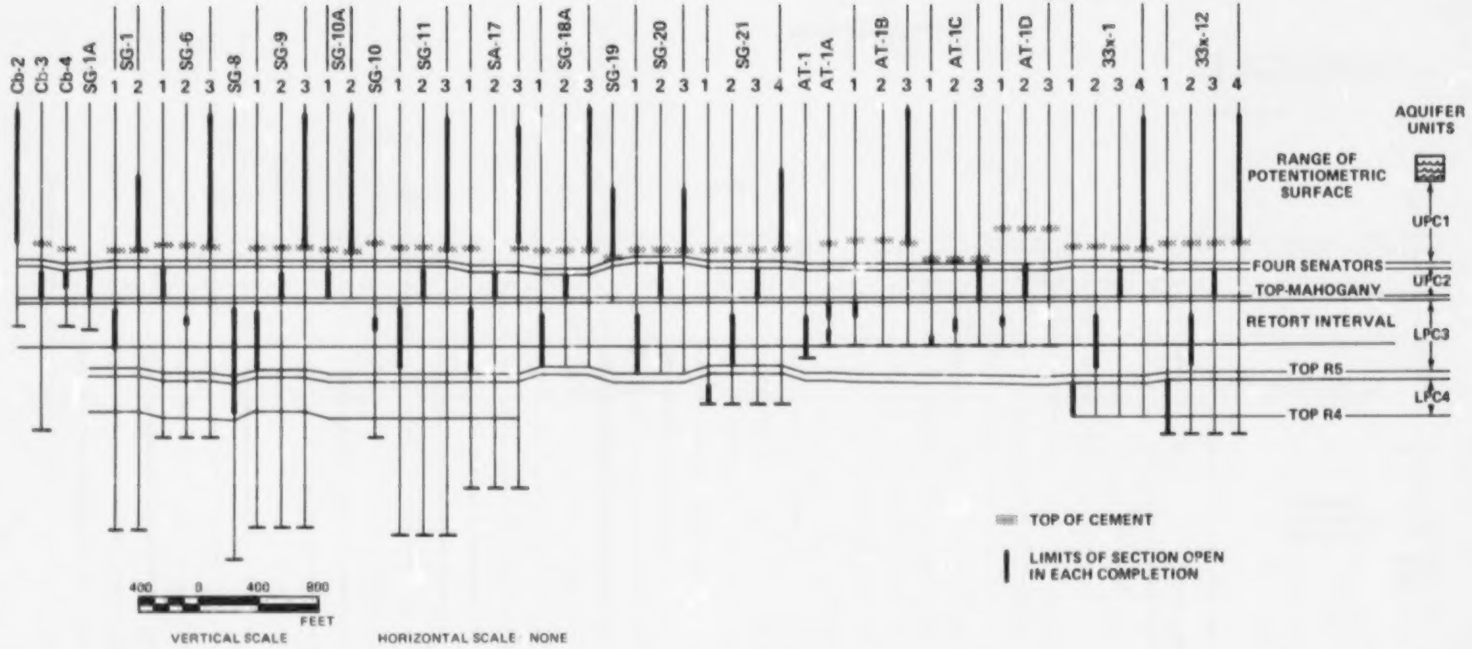
Cb-2
Cb-3
Cb-4
SG-1A
SG-1
SG-6
SG-8
SG-9
SG-10A
SG-10
SG-11
SA-17
SG-18A
SG-19
SG-20
SG-21
AT-1
AT-1A
AT-1B
AT-1C
AT-1D
33x-1
33x-12
AQUIFER UNITS
RANGE OF POTENTIOMETRIC SURFACE
UPC1
FOUR SENATORS
UPC2
TOP-MAHOGANY
RETORT INTERVAL
LPC3
TOP R5
LPC4
TOP R4
TOP OF CEMENT
LIMITS OF SECTION OPEN IN EACH COMPLETION
400
0
400
800
FEET
VERTICAL SCALE
HORIZONTAL SCALE: NONE

Figure 9-8. Planned well completions, subsurface hydrology monitoring program, Tract C-b.

TABLE 9-7. UPPER AQUIFER MONITORING NETWORK (BEFORE RECOMPLETIONS)

Cb-2
Cb-4
AT-1C #3
SG-1 #2
SG-6 #3
SG-8 #2
SG-9 #2
SG-10A
SG-11 #3
SG-17 #2
SG-18A
SG-19
SG-20
SG-21

AFTER RECOMPLETIONS: U_1, UPC_1, UPC_2

CLOSE IN DURING ANCILLARY DEVELOPMENT	REMOTE DURING ANCILLARY DEVELOPMENT
Cb-2 (UPC_1)	Cb-3 (UPC_2)
SG-1 #2 (UPC_1)	Cb-4 (UPC_2)
SG-1A (UPC_2)	SG-9 #2 (UPC_2)
SG-6 #3 (UPC_1), #1 (UPC_2)	SG-11 #2 (UPC_2), #3 (UPC_1)
SG-10a #1 (UPC_2), #2 (UPC_1)	SG-17 #2 (UPC_2), #3 (UPC_1)
SG-20 #1 (UPC_2), #3 (UPC_1)	SG-18A #2 (UPC_2), #3 (UPC_1)
AT-1B #3 (UPC_1)	SG-19 (UPC_1)
33X-1 #3 (UPC_2), #4 (UPC_1)[a]	SG-21 #3 (UPC_2), #4 (UPC_1)
32X-12 #3 (UPC_2), #4 (UPC_1)[a]	

[a] These recompletions have been deleted by developers.

TABLE 9-8. LOWER AQUIFER MONITORING NETWORK (BEFORE RECOMPLETIONS)

Cb-1
AT-1C #1
AT-1C #2
SG-1 #1
SG-6 #1
SG-6 #2
SG-8R
SG-9 #1
SG-10
SG-10R
SG-11 #1R
SG-11 #2
SG-17 #1R

AFTER RECOMPLETIONS: LPC_3, LPC_4

CLOSE IN DURING ANCILLARY DEVELOPMENT	REMOTE DURING ANCILLARY DEVELOPMENT
SG-1 #1 (LPC_3)	SG-9 #1 (LPC_3)
SG-6 #2 (LPC_3)	SG-11 #1 (LPC_3)
SG-10 (LPC_3)	SG-17 #1 (LPC_3)
SG-20 #1 (LPC_3)	SG-18A #1 (LPC_3)
AT-1A (LPC_3)	SG-21 #1 (LPC_4), #2 (LPC_3)
33X-1 #1 (LPC_4), #2 (LPC_3)[a]	SG-8
32X-12 #1 (LPC_4), #2 (LPC_3)[a]	

[a] These recompletions have been deleted by tract developers.

of existing deep wells to correspond to the stratified aquifer configuration and present dewatering plans.

The Lower Aquifer is also a complex system of highly stratified units of different permeability. During the ancillary development stage when the major stress is applied to the aquifers and with subsequent dewatering, existing deep holes on and off tract will be monitored for quality and quantity effects produced by the withdrawal of mine water. A segregation of all lower level mine water and subsequent treatment before discharge are probably required since the quality of this water is poorer than that of the Upper Aquifer water. Figure 9-6 shows the Lower Aquifer subdivided into the LPC_3 and LPC_4 zones. These intervals (especially the LPC_3 subzone) may have to be dewatered for the creation of underground retorts. To monitor the effect of this dewatering, the recompletions of Table 9-8 and Figure 9-6 are necessary. The Mahogany Zone is judged by the C-b Shale Oil Venture to be an impermeable barrier so that potential subsequent dewatering in the LPC_3 and LPC_4 zones would have minimal effects on the upper zones over the short term. As discussed elsewhere in this report, these conclusions on site-specific hydrogeology are open to question.

As in the case of the Upper Aquifer, the deep tubing strings will also be recompleted to correspond to the multiaquifer concept. The wells as presently completed observe the entire "Lower Aquifer" from the Mahogany Zone to the terminal depth of all holes. With the planned completions, these separate units will be isolated and monitored separately.

Deep aquifer wells on Tract C-a are largely dual completions with perforated intervals above and below the Mahogany Zone (Figure 9-9). No more detailed identification and monitoring of aquifer units is included in Tract C-a development plans.

MONITORING EVALUATION

Monitoring deficiencies may be segmented into two general categories:

1. Deficiencies in information (e.g., characteristics of potential pollution sources, potential pollutants, hydrogeology, etc.) needed for the development of a cost-effective monitoring program

2. Deficiencies in sampling with regard to capability for detecting impacts on groundwater quality from specific potential pollution sources (e.g., problems of well location, well completion, sampling frequency, constituents sampled, sampling methods, etc.).

Items identified in each of these two categories are discussed in this section. Several important monitoring deficiencies in Category 1 have been identified in the initial stages of this study. Because of these and because such information is needed to design cost-effective monitoring programs, discussion of Category 2 deficiencies must be considered preliminary.

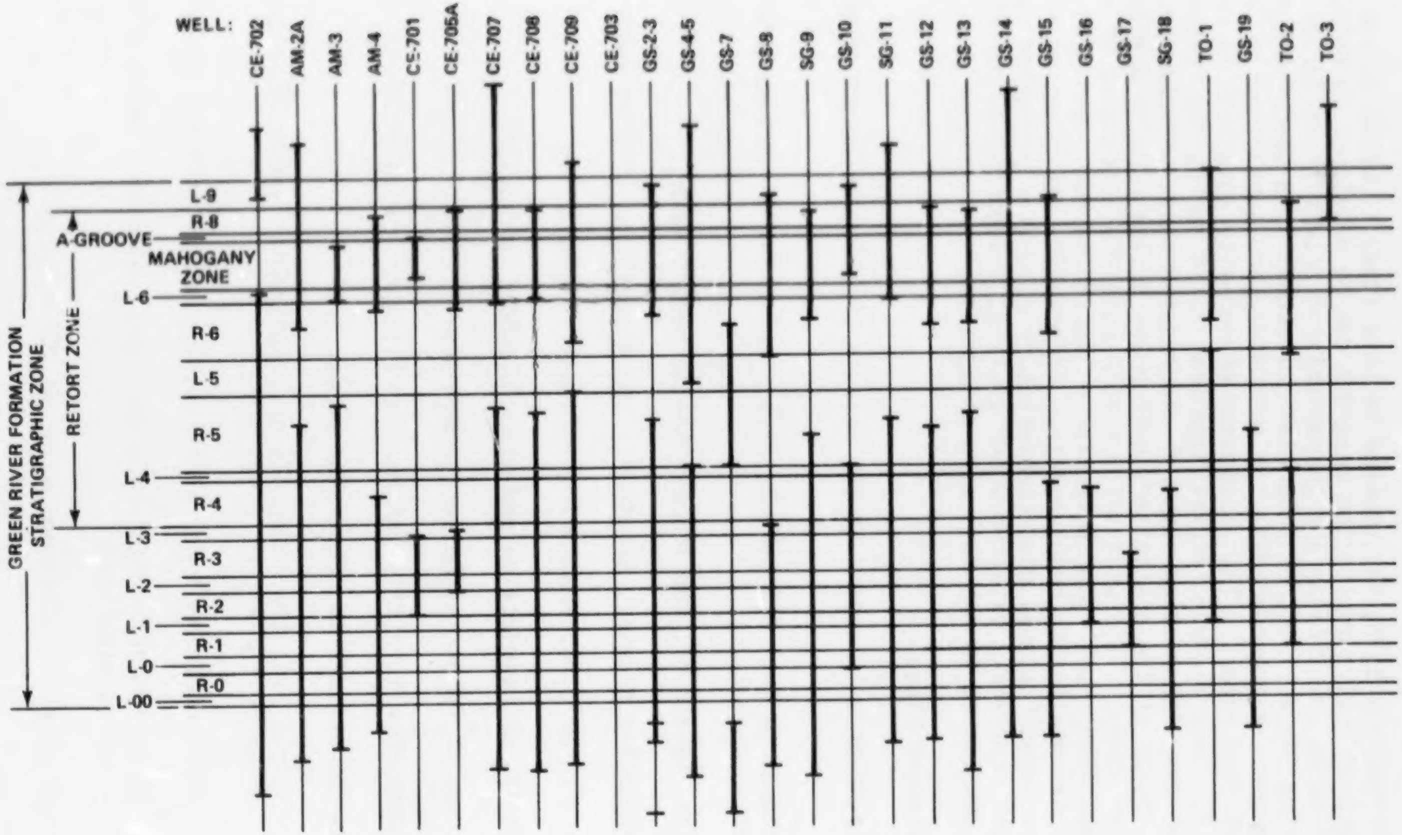

Figure 9-9. Intervals of perforation of wells on tract C-a.

Monitoring Design Information Base

The methodology being implemented in this study is based on the philosophy that cost-effective monitoring programs can be developed by following a sequence of steps identifying and characterizing potential pollution sources and evaluating the mobility of potential pollutants in a specific hydrogeologic framework. Background data for this study are summarized in Sections 1 through 6 of this report. The assessment of mobility potential is considered in Section 7. Several deficiencies have been noted during the review and development of this information summary. Addressing these deficiencies will be the initial focus of the preliminary monitoring design program developed in this phase of study. This will allow a more complete assessment of potential pollutant mobility, ranking of potential pollution sources, and assessment of MIS operational monitoring requirements. Information deficiencies with regard to tract development plans, characteristics of potential pollution sources, hydrogeologic framework, existing water quality, and potential pollutant mobility are considered in the following paragraphs.

Tract Development Plans--

Uncertainties with regard to the details of MIS development plans are as follows:

1. Methods to seal MIS retorts (e.g., injection of surface processed shale)
2. Flow, treatment, and disposition of retort water
3. Collection schemes, treatment, and disposition of mine water
4. Details of other dewatering (via wells) operations
5. Details of reinjection and other disposal operations.

Characteristics of Potential Pollution Sources--

Uncertainties within this information category are as follows:

1. Sealing of in-situ retorts as a result of:
    a. Maintaining the integrity of impermeable layers above and/or below the retort zone
    b. High retorting temperature sealing action on shale minerals
    c. Injection of surface retorted spent shale or other sealing/grouting materials
2. Integrity of rock between adjacent MIS retorts

3. Concentration of condensed shale oil, retort water, or other potential pollutants in the bottom of MIS retorts

4. Chemical characteristics of MIS processed shale leachate from native groundwaters and rates of leaching

5. Chemical characteristics of MIS retort water

6. Leaching characteristics of surface-retorted spent shale if reinjected as a slurry

7. Plans for sampling composition of sources (mine water, dewatering-reinjection well water, retort water, in-situ spent shale).

Hydrogeologic Framework and Existing Water Quality--

Of key importance for the assessment of mobility of pollutants and for the design of operational monitoring programs (e.g., well placement, well construction, and sampling requirements) is knowledge of the hydrogeology and existing water quality of the study area. Several deficiencies have been noted in the understanding of this complex groundwater system. Because great spatial variability in the hydrogeology has been indicated, satisfying data needs should focus on the proposed retort fields:

1. Identification and characterization (hydraulics and water quality) of individual stratigraphic layers:
    a. Isolation of layers using packers for testing and sampling
    b. Identification and testing of corresponding (i.e., continuous) intervals in a series of wells to assess areal variation of hydrogeologic characteristics and water quality
    c. Comparison of available data on well bore production, conductivity, temperature, and velocity logs with lithologic logs to better define zones of water production and quality

2. Investigate nature and extent of upward leakage in northeast corner of Tract C-a

3. Investigate effects of faults as both hydraulic barriers and as routes of interaquifer connection (this particularly for Upper Aquifer on Tract C-a)

4. Sampling proposed (if any) during shaft sinking and lateral development to examine three-dimensional distribution of groundwater quantity (and possibly quality)

5. Examine vertical head gradients and relationships

6. Determine leakance values for confining beds

7. Delineate fracture patterns and location of solution openings

8. Further characterize water quality through examination of, for example, chemical equilibria, stable isotopes, water temperature variations

9. Evaluate influence of alternative sampling methods (bailing, swabbing, pumping) and casing material (e.g., steel) on water quality data

10. Identify rate and direction of groundwater flow.

Potential Pollutant Mobility--

The uncertainties and data deficiencies presented in the preceding paragraphs result in incomplete capability for predicting the mobility of potential pollutants. The preliminary assessment is that important attenuation (e.g., sorption and precipitation) may occur within the retort zone. Attenuation within the existing aquifer zones, however, may not be extensive. Flow pathways, leaching rates, and the characteristics of potential pollutants are among the basic incomplete data sets which have been identified. In addition, the importance of the various attenuation mechanisms outlined in Section 7 is unknown. Addressing such unknowns is the purpose of initial monitoring and testing efforts. Consideration of attenuation mechanisms is an important factor in assessing the utility of tracer or indicator chemical constituents as part of monitoring programs. This topic is discussed in more detail in Section 10 (Monitoring Approaches). Monitoring needs would include:

- Sampling groundwater quality within and adjacent to the retort zone
- Measurement of hydraulic and water quality gradients within the retort zone (e.g., between retort and aquifer zones and between adjacent retorts)
- Using these data to identify important attenuation mechanisms, particularly those which may be purposefully enhanced.

Related to the assessment of attenuation is the monitoring of the rate and direction of transport away from in-situ retorts. Monitoring these processes will be associated with the hydrogeologic characterization of the retort field as discussed earlier.

Existing or Proposed Monitoring Plans

Existing or proposed monitoring plans for Tracts C-a and C-b, as well as for the Piceance Basin in other areas, are summarized earlier in this section. Subsequent discussions have presented uncertainties in the data base needed for the design of a successful monitoring program. Because of these uncertainties, identification of deficiencies in existing or proposed monitoring plans cannot be made in detail. However, as previously noted, some questions have been raised relative to the topics of well completion and sampling procedure. Potential investigations include:

1. Assessment of pumped versus bailed and/or swabbed samples from alluvial wells and from deep wells on tract or elsewhere in the basin
2. Assessment of well completions previously used as to the impact on water quality (this is related to characterization of individual stratigraphic intervals as outlined above)
3. Plans to monitor the mine or within abandoned retorts

SECTION 10

MONITORING APPROACHES

From the preceding discussions, appreciable uncertainties exist with regard to prediction of the impact of MIS retorting on groundwater quality. Major issues relate to:

- Characterization of potential MIS pollutants
- Characterization of mobility pathways and rates, especially within and directly adjacent to the retort interval
- Sampling methods, including well construction and sample collection procedures
- Selection of constituents for monitoring MIS sources.

POTENTIAL POLLUTANTS

The major focus of characterization efforts will be leachates from in-situ spent shale and other residuals (e.g., retort water) remaining in the MIS retort zone after completion of retorting. Although some data from laboratory simulations are available and have been utilized in this study, the applicability of these data to actual MIS operations is unclear. Thus, actual sampling and analysis of MIS retorts are needed. Approaches to address this information requirement are as follows:

- Core or otherwise sample the following for physical and chemical analysis:
    - -- Proposed retort sealing or stabilizing
    - -- In-situ spent shale (examine variability as related to variations in raw shale from the interval retorted and variations in retorting history)
    - -- In-situ retort water
- Perform mass balance inventory for retort water
    - -- Evaluate presence of retort water residue in spent retort

- Evaluate water from mine (compare water quality and quantity near retort before and after retorting)

- Perform leaching experiments with groundwaters of both aquifers in study area to examine rates of leaching and adsorption/attenuation mechanisms. These experiments need to approximate, to the extent possible, time frames (i.e., long) and flow rates (i.e., slow) anticipated in retort zone

- Controlled backflooding of a spent MIS retort cell with analysis of the following:

  - -- Movement into adjacent wells (measurement of head levels, flow rates, water quality, and evaluation of pollutant attenuation)

  - -- Hydraulic characteristics of MIS retort

  - -- Water quality gradients and attenuation within retort zone.

Only the first four of these approaches (sampling within spent retorts and performing leaching experiments) seem feasible. The backflooding experiments would clearly provide the truest test, but the engineering design and control of such an experiment would appear to be prohibitively expensive, even if the experiment were shown to be physically possible.

HYDROGEOLOGIC CHARACTERIZATION

Study Needs

Hydrogeologic studies to date have been largely regional in focus. This has led to a largely regional focus in monitoring plans rather than a near-field, source-specific monitoring orientation, which is more appropriate for pollution detection and control purposes. The indicated great spatial variability in hydrogeologic and water quality characteristics of the study area has resulted in data sets collected to date which may not be applicable to source-specfic monitoring designs (i.e., within and particularly immediately downgradient from the MIS retort fields).

Evaluation of potential mobility pathways requires:

- Detailed analysis of the near-field (relative to MIS retorts) fracture system

- Analysis of three-dimensional variability of hydrogeologic characteristics

- Evaluation of the effects of dewatering, reinjection, retort development, and retort operation on the hydrogeology.

Some approaches for addressing the analysis needs follow:

- Geophysical methods
  - -- Reanalysis of data from tract exploration phases (not included in environmental baseline reports) to evaluate utility for examination of porosity within retort fields
  - -- Potential for additional logging in existing core holes or well bores
  - -- Geophysical logging of new wells proposed for Tract C-b retort field (methods outlined in following discussion)
- Analysis of dewatering (Tract C-a) data (pumping and reinjection)
  - -- Treat as large-scale aquifer test with close-in orientation to retort field
  - -- Evaluate water quality data (particularly variations in water withdrawn from different intervals in aquifer zone)
- Examination during mine excavation
  - -- Examination of fractures near retort interval
  - -- Sample water flow and water quality within mine (pre- and post-retort detonation)
  - -- Possibly coring within mine near retort (e.g., from upper sublevels)
- Further evaluate potential for upward leakage in northwest corner of Tract C-a
- Development of anisotropic flow nets for Upper and Lower (above and below retort zone) Aquifer zones
- Outline testing methods for confined beds (leakance), vertical head gradients, investigation of faults as hydraulic barriers or pathways.

Baseline Data Acquisition

Because of the complex nature of the hydrogeology and geochemistry of the natural groundwater system in the Piceance Basin, considerable additional knowledge will have to be obtained at each specific mining site to allow preliminary estimates of contaminant flow rate and direction to be made and to allow preliminary design of the monitoring system. The required information includes:

1. Delineation of the individual porous and permeable zones, their thicknesses, porosities, permeabilities, potentiometric surfaces, natural water quality, and areal extents

2. Definition of the individual confining layers and their properties

3. Definition of structural geologic features that affect the hydrogeologic system

4. Location of the discharge points for each aquifer (or aquifer unit).

It appears that, in spite of the effort that has already been made to acquire site-specific hydrogeologic data, the information sets listed above are not complete. The field studies that have been performed do, however, establish a basis for design of the more detailed analyses that are needed.

Definition of Individual Porous and Permeable Zones--

Although it has been concluded that, in general, two rock aquifer systems (a shallow and deep one) are present in the Piceance Basin, available evidence shows that the hydrogeology is actually more complex. It appears that porous and permeable intervals exist locally which may or may not be hydraulically interconnected and may or may not conform to the general concept of an Upper and a Lower Aquifer with the Mahogany Zone as the aquiclude between the two. It is extremely difficult to completely address the adequacy of models or groundwater monitoring systems at a specific mining site in the Piceance Basin until the principal porous and permeable zones have been identified locally and their hydraulic properties, potentiometric surfaces, natural water qualities, and areal geometries determined to the extent possible and practical.

In the Piceance Basin, initial identification of porous and permeable zones can probably best be accomplished by downhole methods. Examination of rock units at the outcrop may be of some help, but would not be sufficient alone. The only applicable remote method would be seismic reflection, which can, under the proper conditions, be used to identify and map porous zones. It is judged that conditions in the Piceance Basin are not conducive to the use of seismic reflection for porous zone identification. It might be applied experimentally for areal mapping after identification of such zones by downhole methods.

Downhole methods for identification of porous and permeable zones include:

1. Core drilling

2. Rock drilling

3. Bore hole geophysical logging

4. Injectivity and pump testing

5. Water-level measurements and water sampling.

Core drilling--Drilling of small-diameter core holes is a relatively inexpensive method of locating and characterizing porous zones. Cores can reveal fractures, solution features, and evaporite zones that are subject to solution activity. It is possible that none of these might be recognized in holes drilled with rock bits. Core drilling was performed at each tract in the exploration phase. Cores are sometimes retained and may still be available for inspection. If not, core descriptions may alternatively be available. If neither cores nor descriptions are available, new core drilling at a few selected locations may be worthwhile.

In addition to visual examination, cores can be laboratory tested for porosity, permeability, and other engineering properties. However, laboratory testing of cores taken from aquifers with major fracture or solution porosity and permeability is of little value.

Rock drilling--Information on the location of porous and permeable zones can, possibly, also be obtained during drilling of bore holes with rock bits. During rock-bit drilling, the presence of such zones is indirectly indicated by influxes of water, loss of drilling fluid, changes in drilling rate, change in fluid level in the bore hole, etc. Drillers' logs for bore holes that have already been drilled might yield some information on the presence of porous and permeable zones.

In any case, as new holes are drilled, the drillers should be encouraged to note such occurrences as are mentioned above.

Bore hole geophysical logging--A variety of bore hole geophysical logging tools are commercially available that are useful in defining porous zones. These include:

1. Electrical logs
2. Elastic wave logs
3. Radiation logs
4. Other logs.

The particular logs in each of the categories that detect porosity are noted in the applications column of Table 10-1. It is of particular interest that elastic wave logs can differentiate between fracture or solution porosity and intergranular porosity.

In addition to the logs listed in Table 10-1, such miscellaneous logs as caliper logs, dipmeter logs, and production-injection logs may be used. Production-injection logs are logs normally run through tubing or casing after a well is completed. Some of these logs are the same as listed in Table 10-1, but a number of specialized logs are also used.

The principal applications of production-injection logs are determination of:

TABLE 10-1. GEOPHYSICAL WELL LOGGING METHODS AND THEIR APPLICATIONS

Method	Property	Application
Electrical Logs		
Spontaneous Potential (SP)	Electrochemical and electrokinetic potentials	Formation water resistivity (R_w); shales and nonshales; bed thickness; shaliness
Nonfocused electric	Resistivity	a. Water and gas/oil saturation b. Porosity of water zones c. R_w in zones of known porosity d. True resistivity of formation (R_t) e. Resistivity of invaded zone
Focused conductivity	Resistivity	a, b, c, d. Very good for estimating R_t in either fresh water or oil base mud
Focused resistivity	Resistivity	a, b, c, d. Especially good for determining R_t of thin beds Depth of invasion
Focused and nonfocused microresistivity	Resistivity	Resistivity of the flushed zone (R_{xo}) for calculating porosity Bed thickness
Elastic Wave Propagation Logs		
Transmission	Compressional and shear wave velocities	Porosity; lithology, elastic properties, bulk and pore compressibilities
	Compressional and wave attenuations	Location of fractures; cement bond quality
Reflection	Amplitude of reflected waves	Location of vugs, fractures; orientation of fractures and bed boundaries; casing inspection

(continued)

TABLE 10-1 (continued)

Method	Property	Application
Radiation Logs		
Gamma ray	Natural radioactivity	Shales and nonshales; shaliness
Spectral gamma ray	Natural radioactivity	Lithologic identification
Gamma-gamma	Bulk density	Porosity, lithology
Neutron-gamma	Hydrogen content	Porosity
Neutron-thermal neutron	Hydrogen content	Porosity; gas from liquid
Neutron-epithermal neutron	Hydrogen content	Porosity; gas from liquid
Pulsed neutron capture	Decay rate of thermal neutrons	Water and gas/oil saturations; reevaluation of old wells
Spectral neutron	Induced gamma-ray spectra	Location of hydrocarbons; lithology
Other Logs		
Gravity meter	Density	Formation density
Ultra-long spaced electric	Resistivity	Salt flank location
Nuclear magnetism	Amount of free hydrogen; relaxation rate of hydrogen	Effective porosity and permeability of sands; porosity for carbonates
Temperature	Temperature	Formation temperature, flow direction, relative head

1. The physical condition of subsurface equipment and the bore hole

2. The location of production or injection zones

3. The quantity of fluid produced from or injected into a particular zone

4. The results of well bore stimulation treatment.

Table 10-2 lists some of the available production-injection logs that would have particular application to porous zone identification.

TABLE 10-2. SELECTED PRODUCTION-INJECTION LOGS AND THEIR FUNCTION

Log	Function
1. Gamma-ray	Determine lithology and presence of radioactive tracers through casing
2. Neutron	Determine lithology and porosity through casing
3. Bore hole televiewer	Provide an image of casing wall or well bore
4. Flowmeter (spinner logs)	Locate zones of fluid entry or discharge and measure contribution of each zone to total injection or production
5. High-resolution thermometer	Locate zones of fluid entry including zones behind casing
6. Radioactive tracer	Determine travel paths of injected fluids including behind casing
7. Fluid sampler	Recover a sample of well bore fluids
8. Fluid pressure	Determine fluid pressure in bore hole at any depth

Bore hole logs that have been run in some of the holes already drilled should be obtained and interpreted. Bore holes not previously logged could possibly be logged. Where holes have been steel cased, only radiation logs could be run in the cased portion. Where holes are PVC cased, electrical induction logs could probably also be run in the cased portion of the hole. The particular suite of logs to be run would be dictated by economics as well as technical considerations and would need to be determined in consultation with logging service company representatives.

Injectivity and pump testing--Some aquifer testing has been performed at Oil Shale Tracts C-a and C-b. Additional tests should be made on individual porous and permeable zones, rather than on the gross intervals that have been tested previously. In preparation for testing, the individual zones should be isolated with packers. Monitor wells should also have temporary packers selectively set to test the continuity of individual porous and permeable zones and the extent of their hydraulic interconnection with other adjacent zones. The alternative to using packers would be to construct wells which tap the zone to be tested.

The details of any such testing program will have to be determined after the number, location, thickness, and continuity of the porous zones have been estimated from the other procedures suggested above.

Water level measurements and water sampling--In an undisturbed state, it is quite probable that individual porous and permeable zones had differing hydraulic heads, hydraulic gradients, flow patterns, and water qualities. These characteristics can allow differentiation among zones and tracing of zones. However, it may be difficult or even impossible to reconstruct the original natural conditions for the individual zones because of the amount of interconnection that has occurred as a result of bore holes left open to multiple zones. Any available data should be used in an attempt to depict the most probable undisturbed hydrologic conditions. It may be desirable to modify existing monitoring wells to isolate certain porous and permeable zones. This might allow the hydraulic conditions in such zones to readjust to the original or near-original conditions and would, in any case, permit monitoring of discrete intervals rather than multiple intervals. Multiple zones can be monitored in a single well by use of multiple tubing strings and packers.

A central issue related to the isolation and individual consideration of permeable strata is the scale of this segmentation in a given well design. In other words, at what point do differences in hydraulic or water quality characteristics become significant enough to justify the added expense of multiple completions? At the time of drilling and testing, data can be compiled on gross properties of the well location via use of, for example, drillers' logs, geophysical logs, temperature logs, conductivity measurements, and spinner logs. Data for a series of wells could be collected and compared to identify intervals to be isolated and to obtain consistency between monitor well completions. Further evaluation using injection or pumping tests could be used to finalize the completion schemes. Leaving drilled holes open during this testing and the evaluation process should present no great difficulties in these hard-rock aquifer zones.

These considerations are relevant both to deep aquifer wells and to alluvial aquifer wells. The heterogeneity of deep fractured aquifers is described elsewhere in this report. Significant variability can also be found in alluvial systems. Varying characteristics of alluvial strata can create significant differences in water quality as well as head differences between layers. As with evaluation of deep aquifer well construction, such factors must be carefully considered at each site (or set of well sites) to judge whether it is appropriate or desirable to composite samples over these intervals or if the different intervals should be isolated for separate monitoring.

Properties of Confining Layers--

Just as individual porous zones require more accurate characterization, the individual confining layers should be located and their thicknesses, vertical permeabilities, and lateral extents determined. The procedures will, in general, be the same as those used to define the porous zones except that, during pumping or injection testing, the confining layers are indirectly tested at the same time that the porous zones are being directly tested. Therefore, separate field tests will not normally need to be performed upon the confining layers.

Structural Geologic Features--

Local geologic structure can greatly affect the groundwater hydrology. Faults and fracture zones can act as flow conduits and, on the other hand, faults may cut off porous zones and act as hydrologic barriers. Such structural features are best located by surface and subsurface geologic mapping. The hydrologic effect of geologic structures can be determined by water-level information which is used to construct potentiometric surface flow nets. Potentiometric surface flow nets can reveal the presence of flow conduits or barriers through the configuration of the flow lines. Pump tests or injection tests can directly determine the hydraulic effectiveness of faults or fracture zones to act as flow conduits or of faults to act as flow barriers. Such tests must, however, be designed so that these features will exert a measurable hydraulic effect during the performance of the test.

Aquifer Discharge Points--

To assess the environmental impact of contaminants introduced into the groundwater system by in-situ oil shale combustion, it will be important to locate points at which discharge to surface waters occurs. Discharge points importantly influence the flow pattern and flow velocity in the discharging aquifer. Furthermore, if it can be predicted that contaminants will be discharged to a surface water while still in an undesirable form and concentration, then the contaminants may be viewed differently than if they were to remain contained indefinitely in the subsurface.

Discharge points are located by surface reconnaissance, stream gaging, seepage-salinity surveys, mapping of aquifer water levels, and possibly by introduction of tracers into aquifers and following them to discharge points.

SAMPLING AND ANALYSIS

The facets of monitoring considered under this heading include sample collection methods, selection of constituents for analysis, and data presentation-evaluation programs:

- Compare data obtained from pumping, bailing, and swabbing of deep wells (assess costs as well as data collected)
- Assess influence of Tract C-b well recompletions on water quality (and water-level) data
- Assess influence of casing materials, if possible
- Select constituents for monitoring (testing associated with leaching tests)
    - -- Use of tracers
    - -- Evaluate enrichment factors
    - -- Stable isotopes as tracers

- Assess physical access for monitoring within spent retorts
  - -- Access through bulkheads
  - -- Use of piping from retorting operation
- Assess "survival" of water quality samplers (e.g., salinity sensors, porous cups, etc.) in retort environment (this testing is associated with leaching tests)
- Evalute and test sample-handling procedures (e.g., effects of holding time on analysis results)
- Recommend data-handling methods useful for easy presentation and assessment
- Conduct lab analyses (particularly for process streams, such as retort waters).

Source Monitoring

As noted earlier, groundwater quality monitoring should have a source-specific focus. Needs for monitoring of in-situ retorts, retort water, and dewatering-reinjection, as observed on Tracts C-a and C-b, are outlined below.

In Situ Retorts (Spent Shale)--

Preliminary monitoring recommendations for the in-situ retorts are listed below. Selection of constituents for sampling is considered later in this section.

- Evaluate use of existing wells or core holes, including possible well recompletions to monitor specific zones of permeability around retort fields

  Major disadvantage is that many wells developed for Tract C-a and C-b baseline studies are at some distance from individual retorts or retort fields and hence are the not best sites for monitoring retorts
- Need to sample all significant aquifer units in the vicinity of retorts (e.g., five units were identified for Tract C-b; the Uinta Aquifer has recently been included in an Upper Aquifer unit)
- Need wells in and immediately downgradient from retort fields (neither tract seems well set for this recommendation)
- Need wells which tap retorts themselves. Access may be from within mine or from surface, the former probably being least expensive. Some risk of aquifer interconnection via well bore is possible with such wells.

Retort Water--

Alternatives for monitoring retort water are as follows:

- Monitor volume produced
  - -- Monitoring via in-line flowmeters or sonic-type devices (the latter are probably a better choice because of potential maintenance problems with mechanical devices).
  - -- Monitor at various points (inventory to keep track of retort water): production point (retort), treatment point (if treated), storage site, disposal site. This will not, however, indicate anything about residues condensed and remaining within retorts.
  - -- Monitoring can be continuous or periodic (at least for initial operations, the former is preferable).
- Monitor chemical quality
  - -- Monitor changes at various points (production, treatment, storage, disposal)
  - -- Perform mass balance inventory
  - -- Evaluate use of specific "tracer" constituents or indicator variables
  - -- Evaluate lab methods for analysis.
- Assess variability of retort water flow and quality to define sampling frequency (e.g., use continuous monitoring of flow, conductivity, and pH with more complete analysis on weekly or daily interval). Some such data may be available from Logan Wash where retort waters are sampled daily.
- Assess flow and water quality variability between retorts.

Mine Water/Dewatering--

Monitoring of mine water and dewatering/reinjection systems includes both within-the-mine and well monitoring components. Many of these sampling programs are related to area hydrogeologic and water quality assessments discussed earlier:

- Monitoring of in-mine collection systems
  - -- Flow rates from different parts of the mine
  - -- Water quality from different parts of the mine

  - Sample during mine shaft and mine lateral and sublevel construction

- Dewatering/reinjection wells
  - Initial analysis to evaluate mass balance and flow
  - Follow area water levels to further evaluate hydrogeology (e.g., assess fractured intervals, perched zones, etc.).

The monitoring approaches appropriate for disposal well systems are presented below (from Warner, 1975). Two major approaches are outlined: monitoring the injection well itself and using outlying monitoring wells. The latter may be the most appropriate. The injection well itself may be the most likely route of unexpected release of injected water:

- Surveillance of injection well
  - Allow estimates of distance of injected water travel (from well pressure (head) and hydraulic properties of injection zone)
  - Interpretation of pressure data
  - Record of injection activity
- Quality of injection water
  - Continuous, perhaps suspended solids, pH, conductivity, temperature, dissolved oxygen
  - Composite or grab samples periodically for more complete characterization
- Injection pressure-record of reservoir performance
  - Continuous monitoring (want to avoid hydraulic fracturing, damage to well facilities)
  - Collect and evaluate pressure fall-off data to check reservoir performance
- Pressure in casing-tubing annulus
  - Changes may indicate leakage through injection tubing or packer systems
  - Use conductivity probe to check chemistry of casing-tubing annulus to check for leaks
- Periodic inspection and testing

- -- Casing, tubing cement
    - • Pull tubing (visual or instrument inspection)
    - • Use logs to inspect in place (e.g., magnetic logs for relative pipe thickness; televiewer logs for visual inspection; or caliper logs for plugging or enlargement of casing)
- -- Inspect casing cement with cement bond or temperature logs to detect channels in cement behind casing
- -- Inspect casing, cement, or well bore with injectivity or temperature profiles or tracer injectivity profiles to detect where injected fluid is going

- ● Monitoring wells
  - -- Monitor pressure in receiving aquifer; pressure at a known distance may be of concern due to suspected faults, poorly plugged abandoned wells, or other unaccounted for pathways of release of injected waters
  - -- Useful for verifying rate and direction of flow of injected water or geochemical changes due to injection program
  - -- Useful to monitor pressure changes within confining beds or in a confined aquifer immediately above confining bed when:
    - • Confining beds are relatively thin
    - • Aquifer properties are such that pressure responses will be rapid if leakage occurs (slow vertical leakage through multiple fracture layers in oil shale area may reduce utility of this approach)
  - -- Use monitoring wells in overlying (relatively good quality) aquifer to detect water quality changes (best placement is close to injection well(s) and near other deep wells or near fault or fracture zone which may be vertical flow paths for injected water).

Warner (1975) also notes that the injection well itself may be modified to sample overlying aquifers through the use of multiple completions in the same well.

Factors Affecting Sampling

The methodology being used in this study provides a logical framework for design of groundwater quality monitoring programs, including selection of sampling sites, well construction features, sample collection methods, and sampling frequency. In the oil shale regions, the complexity of the hydrogeologic systems encountered can present some special problems with regard to these monitoring components.

Sampling Sites--

Groundwater flow in the Piceance Creek Basin occurs in several complex systems of fractures and faults. The evaluation of a fractured-rock flow system is generally much more complicated than assessment of a granular, porous media type of aquifer system. In fractured-rock systems, even defining the direction of flow may not be straightforward. Generally, the direction of flow and the flow gradient in groundwater systems are identified by measuring the head (or water level) in a set of wells and estimating lines of equal head. Flow then is perpendicular to these equipotential lines (Figure 10-1). However, flow in fractured rock is along fractures and these flow paths can provide a flow direction which is nearly perpendicular to that which may be estimated from simple observation of head levels (Figure 10-2). Using this illustration (Figure 10-2), placing a well at point B to monitor the effects of an injection well or other waste source at point A would clearly not produce data which address the defined information requirements. The need for detailed hydrogeologic evaluation is thus an integral part of the monitoring design methodology.

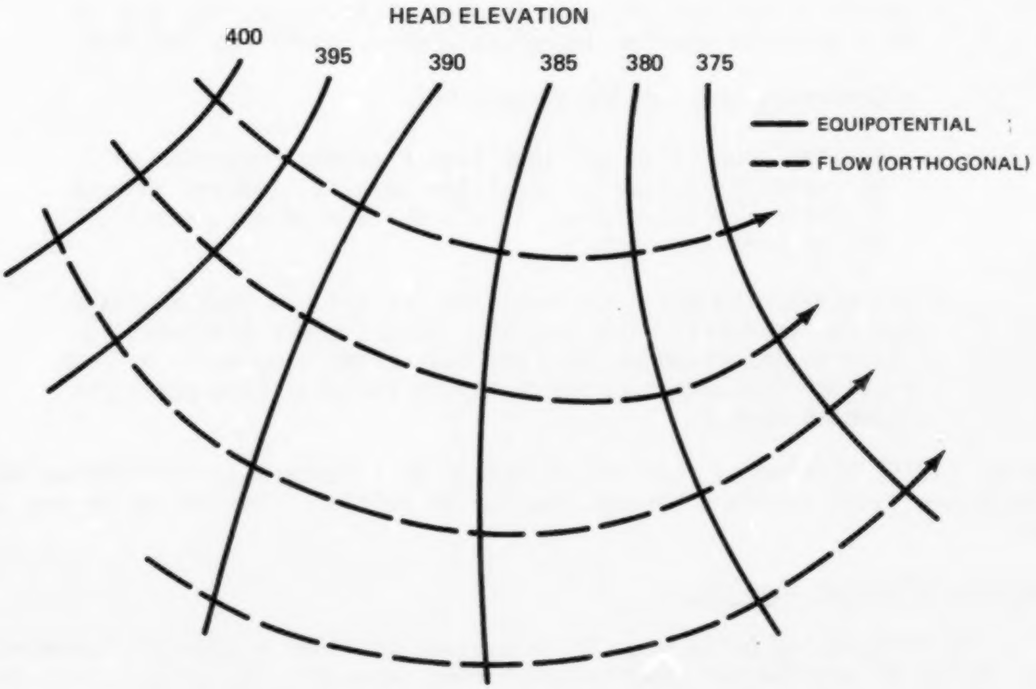

Figure 10-1. Sample of groundwater flow net.

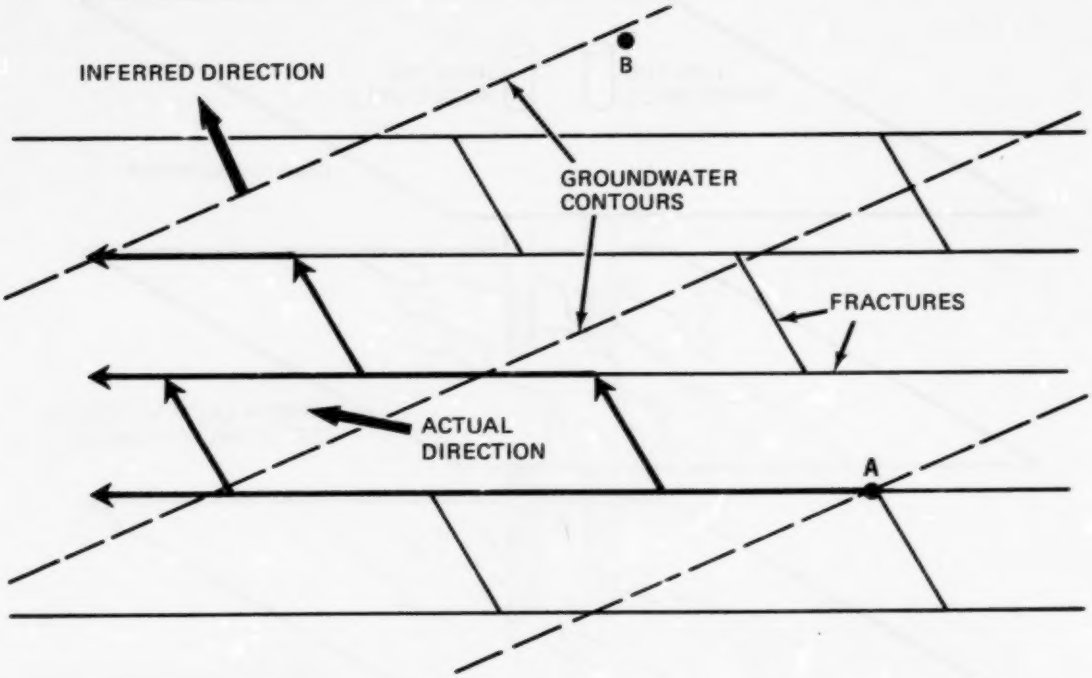

Figure 10-2. Idealized two-dimensional pattern showing the relation between true direction of groundwater flow and the direction inferred by drawing orthogonal lines to the regional water-level contours (adapted from Davis and DeWeist, 1966).

Well Construction--

The aquifer systems in the Piceance Basin include a series of horizontal fracture sets very irregularly interconnected by vertical fractures and faults. The system has commonly been portrayed as including two aquifers separated by the rich oil shale beds of the Mahogany Zone. In actuality, the irregular spacing of both vertical and horizontal fractures, the appreciable variability of hydraulic properties among these fracture sets, and the varying degrees to which halite and nahcolite minerals have been leached from different zones create numerous distinct aquifer units. Where wells are located and where they are perforated (open to water-bearing zones) have a significant influence on the data collected. This is true for data on both aquifer characteristics and groundwater quality.

Consider, for example, two wells located close together and which are perforated over exactly the same interval. The perforated interval contains two fractured strata of equal hydraulic conductivity (Figure 10-3). One stratum contains abundant saline minerals and the other little. One well intersects a fracture in the upper stratum but none in the lower (saline stratum), while the other intersects a fracture in only the lower stratum. These two wells will provide drastically different water quality data in spite of their proximity and construction similarity.

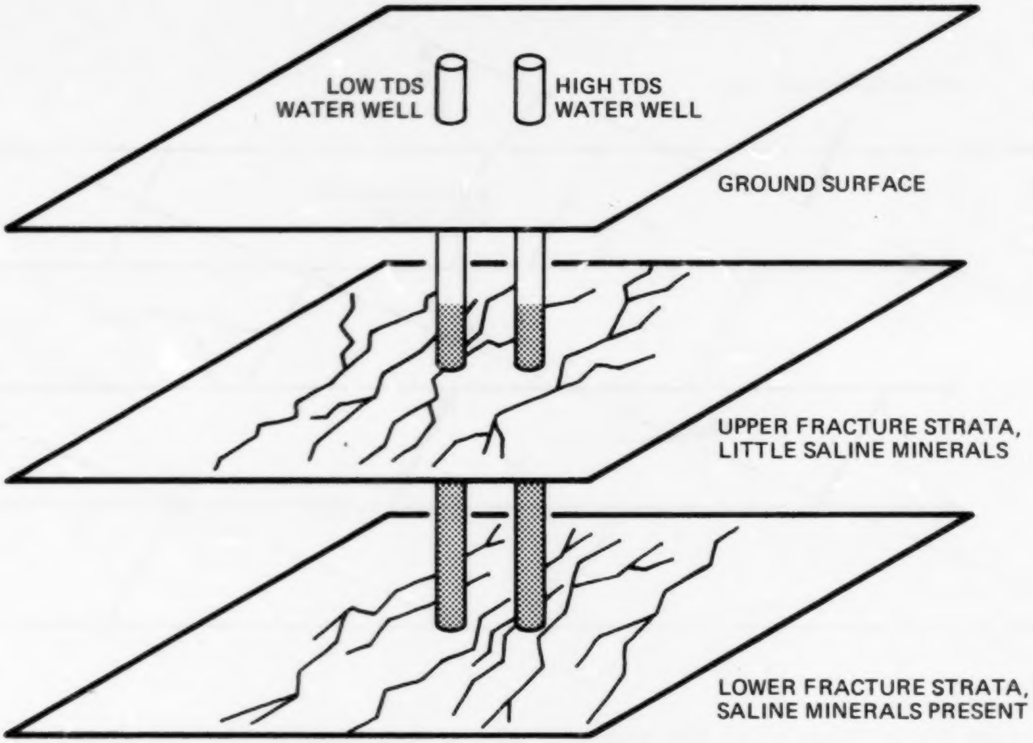
LOW TDS WATER WELL
HIGH TDS WATER WELL
GROUND SURFACE
UPPER FRACTURE STRATA, LITTLE SALINE MINERALS
LOWER FRACTURE STRATA, SALINE MINERALS PRESENT

Figure 10-3. Fractured-rock aquifer system yielding water of varying quality depending on location and perforation of wells.

This situation may be further complicated by varying permeabilities of different strata. Some fine-grained, high-organic-level strata are resistant to fracturing and may form effective aquitards. This can result in different head levels between layers and mixing of highly different quality waters in interconnections, such as well bores. As an example of how well completion (and recompletion) can affect water quality data, consider the following data reported for Tract C-b (C-b Shale Oil Venture, 1977b).

Original well designation	TDS before recompletion	TDS after recompletion	New well designation
SG-11-1	39,000	16,000	SG-11-1R
SG-10	42,000	2,800	SG-10R
SG-17-1	28,000	4,300	SG-17-1R

These wells had initially encountered, and had been open to, a highly saline water zone which apparently had a higher hydrostatic head than less saline overlying aquifer zones. Thus, water collected from these overlying zones was affected by the interconnection. Recompletions were undertaken to isolate these different water quality zones.

Also, interval of completion and perforation may affect water-level data. For example, on Tract C-b, an apparent mound of water in the center of the tract may be due to data from a well (SG-6) completed over a small segment of the aquifer zone. If this interval has a high head, then this well will show a greater head level than other wells in the area which are perforated over a wider zone and thus exhibit a more average head.

Sample Collection Methods--

Methods currently being used to collect groundwater samples on the oil shale tracts include bailing, swabbing, and pumping. The choice of sampling method can greatly influence the results of water quality sampling and thus the interpretation of monitoring data.

On Tract C-a, all groundwater quality samples are collected by bailing. Sufficient water is bailed to fill the required sample bottles. One of the goals of sampling is to obtain water quality data which are representative of water within the aquifer zone being sampled. Aside from problems of well completion, bailing of a small volume from a well bore may not provide the desired representative sample. For example, construction of deep wells may include a perforated zone of perhaps 300 feet. A 6-inch casing, 300 feet long, contains about 450 gallons of water. If approximately 4 gallons are bailed for sampling, for example, on a quarterly basis, water sampled may not be representative of local groundwater, but rather of water which has been standing in the well bore (perhaps a very different physiochemical environment) for some time.

The implication here is that care must be taken with the use of bailing as a sampling technique. For example, tests conducted by Rio Blanco Oil Shale Project (Tract C-a) indicated that samples bailed from well intervals perforated in aquifer zones produced results very comparable to pumped water samples. However, samples bailed from the well interval above the perforated zone (and where water is stagnant within the well) yielded water quality data quite different from either pumped samples or samples bailed from the aquifer zone.

Swabbing, which is used to collect samples from deep aquifers on Tract C-b, includes the use of oil field equipment to collect water samples. Several swabbing runs, removing the water column from the well bore, are made prior to collection of samples for laboratory analysis. This approach may provide water quality samples more representative of local aquifer conditions than bailing, as several well volumes are removed prior to actual sample collection.

Care must also be taken with the swabbing techniques so that contamination of samples (such as from organics from the oil field equipment) does not occur. In addition, the swabbing action may accelerate the plugging of well perforations by the action of the rubber swabbing cup on the casing. The amount of water swabbed from a well must be carefully considered to obtain consistent and representative samples. Variations in water quality (conductivity) observed during swabbing are shown in Table 10-3.

TABLE 10-3. RANGE OF CONDUCTIVITY OBSERVED AND FINAL CONDUCTIVITY LEVEL OF SWABBED SAMPLES, TRACT C-b, FALL 1976

Well/string number	Gallons swabbed	Observed conductivity range (µmhos/cm)	Final conductivity (µmhos/cm)
SG-1-1	1,260	3,000 - 10,000	8,250
SG-1-2	2,840	1,200 - 1,500	1,250
SG-9-1	2,100	1,300 - 3,400	2,000
SG-9-2	1,150	1,850 - 2,100	1,850
SG-21	3,210	750 - 1,150	1,000
Cb-4	2,300	800 - 900	825
SG-11-12	1,220	14,000 - 32,000	22,000
SG-11-2	530	800 - 4,000	1,200
SG-11-3	300	1,600 - 1,800	1,790
SG-18A	---	750 - 1,250	1,000
Cb-2	2,920	1,600 - 1,650	1,600
SG-6-1	550	1,800 - 3,100	3,000
SG-6-2	630	1,300 - 1,400	1,300
SG-6-3	160	1,350 - 1,550	1,550

Many of the difficulties of obtaining representative samples by bailing or swabbing are overcome by use of a submersible pump to collect samples. By pumping, a relatively large area of the aquifer is sampled rather than a zone within or immediately adjacent to the well bore. This "sampled zone size" is an important consideration for monitoring purposes, as well as for general collection of representative samples. For example, assume a well is perforated throughout the water-bearing zone (Figure 10-4). Bailing will sample essentially the width of the well bore, perhaps 6 or 8 inches of the aquifer cross section. Swabbing would sample a wider cross section (perhaps a few feet) and pumping the widest cross section (perhaps several tens of feet). Obviously, the opportunity of detecting the mobility of potential pollutants is enhanced by sampling a greater cross section of the aquifer.

Care must also be taken in the design of sampling programs which include pumping. As shown in Table 10-4, water quality can vary greatly as pumping continues. A schedule of pumping time before sample collection has to be established, largely by trial sampling of each well and frequent sampling of, for example, conductivity and pH, in the field during pumping.

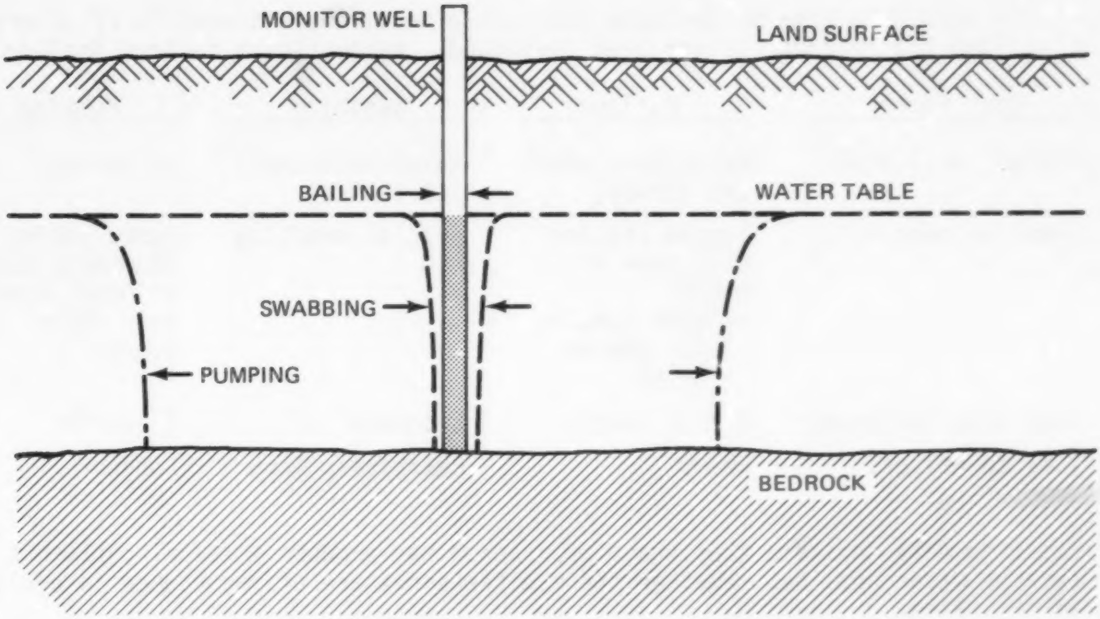
MONITOR WELL
LAND SURFACE
BAILING
WATER TABLE
SWABBING
PUMPING
BEDROCK

Figure 10-4. Schematic of size by aquifer cross section sampled by bailing, by swabbing, and by pumping of monitor well.

TABLE 10-4. FLUORIDE AND BORON FROM LOWER AQUIFER TEST (C-b Shale Oil Venture, 1977b)

Date (1975)	Fluoride (ppm)	Boron (ppm)
January 20	18.0	0.65
February 5	18.1	0.88
February 23	20.0	1.15
February 24	20.1	1.10
February 25	20.4	1.13
February 27	18.4	1.2
February 28	20.4	1.6
March 1	20.2	1.42
March 3	19.0	2.58
March 5	20.0	2.02
March 7	21.2	2.18
March 19	23.2	2.00

A good data base to evaluate the cost-effectiveness tradeoffs of alternative sampling methods has not been developed. Various cost factors include:

Cost factor	Bailing	Swabbing	Pumping
Minimum well size	Relatively small (<3 inches)	Relatively small (<3 inches)	>4 inches
Sampling gear	Sample (bailer plus rope or cable) -- more complex for deeper holes	Special swabbing rig	Pump, cable, discharge pipe or hose, electric power source
Crew size (minimum)	1 to 2 people	3 people	2 people
Time to collect sample*	Short	Relatively long	Longest

Existing data indicate that these approaches may produce somewhat different data on water quality. Whether these differences are of importance is unclear at this time.

Sampling Frequency--

Defining an appropriate sampling frequency is a complex issue influenced by location of sampling sites, monitoring goals, climatological factors, and characteristics of groundwater flow. As a result, sampling frequency should be defined on a case-by-case and likely trial-and-error basis. One of the key factors is groundwater flow rate. If flow from a potential pollution source to a monitoring well is expected to be on the order of decades (assuming a release occurs), then very frequent sampling does not seem warranted and perhaps annual sampling for a few indicator constituents would suffice.

The complexity of the hydrogeology of the oil shale region makes estimation of groundwater flow rate difficult at best and the actual flow rates highly site specific. Table 10-5 lists some estimates of travel time in the Upper Aquifer zone of the Piceance Creek Basin. The wide variation in results reinforces the care needed in design of monitoring programs, as our understanding of the system is incomplete.

Casing Material--

Casing material (e.g., PVC or steel) can also affect water quality data. PVC is preferred to avoid contamination of samples with metal casing corrosion products or adsorption of dissolved constituents onto corroded casing walls. However, the structural properties of PVC may preclude its use for very deep wells. Open-hole (uncased) intervals, which are isolated above and below by

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* Actual time to collect sample for analysis is dependent on amount of water removed from well prior to sample collection.

TABLE 10-5. FLOW RATES OF THE UPPER AQUIFER, PICEANCE CREEK BASIN, ESTIMATED BY THREE STUDIES

Study reference	Flow velocity (feet per day)	Travel time (years to travel 1 mile)
Lawrence Berkeley Labs, 1978 (data from Weeks et al., 1974)	0.05	300
U.S. Atomic Energy Commission, 1972	0.36 - 0.78[a]	20 - 40
Knutson, 1973	11.7	1.2

[a] Range for representative gradient and maximum gradient cases.

packers and/or cement seals and which may be assessed by PVC lines, may be one way of dealing with these problems. Expense of construction and potential for lodging of equipment (pumps) in the well may, however, limit this approach.

Operational Matters--

Related to sample collection is the analysis of water quality samples in the field. As described above, such analyses (e.g., conductivity and pH) are a key element of deciding when to collect pumped, bailed, or swabbed samples. Records of volumes of water withdrawn from a well and water quality data (perhaps in graphical form) should be utilized by field crews during sampling operations. This is needed to assure collection of consistent water quality samples.

Selection of Constituents for Monitoring

The proper location of monitoring points is largely determined by the locale and character of the potential sources of groundwater quality impact and the source locale hydrogeology. The constituents for monitoring are selected so as to provide a cost-effective indication of the nature and extent of impact on groundwater quality. Assessment of enrichment factors (or concentration change above ambient), specific indicator constituents, and stable isotopes are possible approaches for selection of constituents for chemical analysis.

Enrichment Factors--

In this subsection, enrichment factors, EF, will be calculated for major possible sources of groundwater impact according to the expression:

$$\mathrm{EF} = \frac{\text{concentration from potential pollution source}}{\text{concentration in aquifer}}$$

For this assessment, representative baseline water quality levels were selected (Table 10-6). Concentrations from the more saline sections of the Lower Aquifer are included principally in Table 10-6 in order to most clearly demarcate the differences in enrichment factors. Representative concentrations of constituents in retort water and in spent shale leachate were used in this preliminary analysis.

Also shown in Table 10-6 are the lowest concentrations typically reported by a Denver water quality laboratory employing standard methods. As can be seen, the average concentrations of P, V, Ti, As, Se, Ni, Co, Cu, Cd, Br, Be, Ba, and As are close to or below these lower limits. It is therefore likely that many of these trace element species were determined by spark source mass spectroscopy with the associated improvement in detectability, but degradation in precision in comparison to standard methods.

Table 10-7, which lists enrichment factors for the Lower Aquifer, is pertinent to the contamination of the Upper Aquifer, springs, and seeps by the Lower Aquifer. As can be seen, NH_4, K, Na, B, and Br are enriched at least 10 times in the Lower Aquifer compared to either the Upper Aquifer or spring waters. In addition, Ba and F are enriched in the Lower Aquifer compared to spring waters. It is likely, therefore, that these species would be indicators of intrusion of waters from the Lower Aquifer.

Table 10-8 lists enrichment factors for leachates and shows that the parameters OH (or pH), TDS, Cl, Na, SO_4, Mo, Se, and TOC are likely indicators (i.e., tracers) of contamination in the Lower Aquifer. Although carbonate appears to be enriched in leachate, this reflects an increase in pH rather than an increase in total $HCO_3 + CO_3$.

Note that these enrichments are consistent with Equations 1 through 9 expected of a calcined product (Section 7). Sulfate is an expected product of Equation 3. Increased Mo, Cr, and Se are expected from Equations 7 through 9, especially since they form soluble anions under basic, oxiding conditions.

The uncertainty in the enrichment factors reflects variations in the original oil shale, methods of retorting, and methods of analysis, and emphasizes the necessity of preliminary, controlled experiments prior to finalizing monitoring programs. Enrichment factors for those elements which are present in concentrations near the detection limit, such as Se, would also be expected to give variable enrichment factors.

Table 10-9 presents enrichment factors for retort waters and is relevant to the extent that an in-situ retort is not completely burned and retains a fraction of the retort water. Most notably enriched in the retort water are NH_4^+, $CO_3^=$, As, Br, Co, Hg, Se, V, U, and TOC, and possibly NO_3^-, PO_4^{3-}, and Ni. The sulfur species shown at the bottom of the table will be discussed in the next subsection.

Although $CO_3^=$ is enriched in retort waters, it is unlikely that this species would successfully pass through a spent retort because of the reaction:

TABLE 10-6. REPRESENTATIVE CONCENTRATIONS IN GROUNDWATERS ADAPTED FOR THIS STUDY

	Springs, seeps and alluvial aquifer	Upper Aquifer	Saline Lower Aquifer	Lower working limit of detection, Denver Laboratory[a]
Gross Parameters (mg/l)				
Conductance (μmho/cm)	1,300	1,500	7,000	2
pH	6 - 8	7 - 8.5	8	---
TDS	900	1,000	6,000	1
Ammonia	0.4	0.5	10	100
Bicarbonate	500	500	4,000	5
Calcium	70	50	200	0.05
Carbonate	3	3	20	5
Chloride	10	10	20	0.2 - 1
Cyanide	0.01	0.01	0.01	0.002
Magnesium	70	70	20	50
Nitrate	2	1.0	0.5	0.02
Potassium	2	2	20	0.1
Silica	20	20	10	1
Sodium	150	200	2,500	0.1
Strontium	2	2	---	0.01
Sulfate	350	350	60	3 - 10
Phosphate	<0.1	<0.1	<0.1	0.1
Kjeldahl nitrogen	2	---	---	0.1
Nitrite	0.2	---	---	0.02
Sulfide	0.2	0.6	0.6	0.1
Minor and Trace Elements (μg/l)				
Aluminum	300	200	250	100
Arsenic	5	10	10	2 - 50
Barium	50	100	800	50
Beryllium	<100	<10	---	5
Boron	500	1,000	40,000	50
Bromine	20	50	500	2,000

(continued)

TABLE 10-6. (continued)

	Springs, seeps and alluvial aquifer	Upper Aquifer	Saline Lower Aquifer	Lower working limit of detection, Denver Laboratory[a]
Minor and Trace Elements (μg/l) (continued)				
Cadmium	17	10	5	2
Chromium	11	2 - 300	10	5 - 10
Cobalt	8	3	5	10
Copper	30	70	70	10
Fluoride	400	7,000	20,000	100
Iron	500	500 - 5,000	800	10
Lead	50	10 - 100	100	1 - 10
Manganese	30 - 500	100	100	5
Mercury	0.4 - 3	0.4 - 3	0.4 - 2	0.02
Molybdenum	40	50	50	5
Nickel	30	20	10	10
Radiation, alpha (pCi/l)	5	5	20	---
Radiation, beta (pCi/l)	4	4	20	---
Rubidium	10	20	70	---
Scandium	4	---	---	---
Selenium	<10	<10	<10	5
Silver	<1	10	10	0.05 - 10
Thallium	---	---	---	5 - 50
Titanium	200	100	100	300
Uranium	---	<30	<20	---
Vanadium	5	2	16	5
Zinc	200	200	200	5
Lithium	<100	---	---	5
Gross Organic Parameters				
TOC (mg/l)	5	3	10	1
Phenol (μg/l)	3	3	1 - 10	1
DOC (mg/l)	5	8	20	---
COD (mg/l)	16	18	13	10

[a] Using standard methods.

TABLE 10-7. SPECIES ENRICHED IN THE LOWER AQUIFER

	Enrichment factors	
	Lower Aquifer	Lower Aquifer
	Upper Aquifer	Springs and seeps
Conductance	4.6	5.4
TDS	6	6.6
Ammonia	20	25
Bicarbonate	8	8
Calcium	4	4
Potassium	10	10
Sodium	13	17
Barium	8	16
Boron	40	80
Bromine	10	25
Fluoride	2.9	50
Phenolics	0.3 - 10	0.3 - 10

TABLE 10-8. ENRICHMENT FACTORS ESTIMATED FOR SPENT MIS OIL SHALE LEACHATE

	Enrichment factors	
	Leachate	Leachate
	Upper Aquifer	Lower Aquifer
Gross Parameters		
Conductance	2.5 - 52	0.54 - 11
pH	0.6 - 2	0.6 - 1.5
TDS	6 - 140	1 - 23
Bicarbonate	0.2 - 0.4	---
Calcium	0.2 - 60	0.05 - 16
Carbonate	330 - 1,000	50 - 150
Chloride	6.4 - 310	3.2 - 160
Cyanide	---	---
Magnesium	0.01 - 67	0.05 - 235
Nitrate	---	---
Potassium	2.5 - 70	0.25 - 7
Silica	0.5 - 1.0	1.0 - 2.0
Sodium	0.37 - 180	0.03 - 14
Strontium	---	---
Sulfate	0.51 - 260	3 - 1,500
Kjeldahl nitrogen	---	---
Sulfide	1.6 - 3.3	1.6 - 3.3
Minor and Trace Elements		
Aluminum	---	---
Arsenic	0.20 - 20	0.20 - 20
Barium	0.6 - 1.0	0.08 - 0.13
Beryllium	---	---

(continued)

TABLE 10-8. (continued)

	Enrichment factors	
	Leachate Upper Aquifer	Leachate Lower Aquifer
Minor and Trace Elements (continued)		
Boron	0.4 - 12	0.01 - 0.3
Bromine	---	---
Cadmium	0.3 - 0.6	0.6 - 1.2
Chromium	0.01 - 4	0.4 - 130
Cobalt	---	---
Copper	0.14 - 2.9	0.14 - 2.9
Fluoride	0.001 - 11	0 - 4
Iron	0.12 - 6	0.8 - 3.8
Lead	---	---
Manganese	0.6 - 5	0.6 - 5
Mercury	0.10 - 0.8	0.15 - 0.8
Molybdenum	1.5 - 4,000	4 - 1,500
Nickel	2.5 - 30	5 - 60
Rubidium	---	---
Scandium	---	---
Selenium	0.5 - 200	0.5 - 200
Silver	---	---
Thallium	---	---
Titanium	---	---
Uranium	---	---
Vanadium	1.5 - 50	0.19 - 6.3
Zinc	0.1 - 15	0.1 - 15
Gross Organic Parameters		
TOC	10 - 550	3 - 170
Phenolics	---	---

TABLE 10-9. ENRICHMENT FACTORS FOR RETORT WATERS

	Enrichment factors	
	Leachate	Leachate
	Upper Aquifer	Lower Aquifer
Gross Parameters		
Conductance	10 - 130	2.1 - 27
Alkalinity	19 - 130	2.4 - 17
pH	1.0 - 1.6	1.0 - 1.2
TDS	1.8 - 25	0.3 - 4
Ammonium	3,400 - 26,000	170 - 1,300
Bicarbonate	34 - 62	4 - 8
Calcium	0.01 - 1.2	0.002 - 0.31
Carbonate	170 - 10,000	25 - 1,600
Chloride	0.002 - 80	0.001 - 40
Cyanide	40 - 90	40 - 90
Magnesium	0.001 - 5	0.01 - 20
Nitrate	0.17 - 120	0.34 - 240
Potassium	1.5 - 35	0.15 - 3.5
Silica	0.02 - 8	0.04 - 15
Sodium	0.001 - 22	~0 - 1.7
Sulfate	0.06 - 5.4	0.3 - 30
Phosphate	0.8 - 1,000	0.8 - 1,000
Kjeldahl nitrogen	1,700	---
Sulfide	0.17	0.17
Minor and Trace Elements		
Aluminum	---	---
Arsenic	2.4 - 600	2.4 - 600
Barium	0.2 - 7	0.003 - 0.9
Beryllium	---	---
Boron	0.26 - 9	0.01 - 0.22
Bromine	0.4 - 50	0.04 - 5
Cadmium	0.1 - 1.6	0.20 - 3.2
Chromium	0.07 - 60	2.0 - 12
Cobalt	0.4 - 130	0.7 - 220

(continued)

TABLE 10-9. (continued)

	Enrichment factors	
	Leachate	Leachate
	Upper Aquifer	Lower Aquifer
Minor and Trace Elements (continued)		
Copper	0.04 - 1.3	0.04 - 1.3
Fluorine	0.05 - 9	0.02 - 3
Iron	0.00001 - 15	0.001 - 100
Lead	0.05 - 10	0.4 - 10
Manganese	0.23 - 1.4	0.23 - 1.4
Mercury	3.3 - 1,000	5 - 1,000
Molybdenum	2 - 11	2 - 11
Nickel	3 - 50	6 - 100
Radiation, beta	9 - 35	1.8 - 7
Scandium	---	---
Selenium	>0.5 - >170	>0.5 - >170
Silver	---	---
Thallium	---	---
Titanium	2 - 21	2 - 21
Uranium	>0.33 - >150	>0.50 - 230
Vanadium	2 - 5,500	0.25 - 700
Zinc	0.20 - 25	0.20 - 25
Lithium	---	---
Organic Parameters		
TOC	10,000	3,000
Unusual Sulfur Species		
Total sulfur	6 - 20[a]	35 - 120[a]
Thiosulfate	1,200 - 6,400[b]	1,200 - 6,400[b]
Tetrathionate	400[b]	400[b]
Thiocyanate	65 - 2,000[b]	65 - 2,000[b]

[a] Calculated by assuming that all S in groundwaters (Table 10-3) is present as sulfate.

[b] Calculated by assuming background concentrations equal to a detection limit of 0.5 mg/l.

$$Ca^{2+} + CO_3^{=}\ CaCO_3$$

In fact, Parker et al. (1977) have shown that spent shale does, in fact, remove carbonate from surface waters. NH_4^+, on the other hand, is likely a highly mobile species, possibly after conversion to nitrate. In addition, the more hydrophilic portions of the TOC may also travel with leachate and prove indicative of groundwater contamination.

As in leachates from spent shale, retort waters appear enriched in those species forming soluble anions, such as As, Br, Se, and U. The origin of Co, Hg, and V in the retort waters is less clear, although V is known to form organic complexes with organic compounds found in crude petroleum oils, and Hg is known to vaporize from a simulated in-situ retort and to recondense later (Fox et al., 1978b).

In summary, the water quality parameters pH, TDS, Cl, Na, SO_4, Mo, Se, NH_4, Br, Se, V, U, and TOC should be considered as potentially valuable indicators of groundwater contamination, both for their elevated enrichment factors and for chemical reasons.

The utility of enrichment factor estimates is the identification of chemical species likely to be detected in groundwaters which indicate the impact of a known source. To evaluate this possible monitoring approach, the enrichment factors calculated above were categorized (arbitrarily) as follows:

Table 10-1 category	Enrichment factor range	Relative likelihood of detection of impact
1	>500	High
2	50 - 500	Moderate
3	10 - 50	Low

The results of this categorization are shown in Table 10-10.

For monitoring in the Upper Aquifer for the impact from two major in-situ sources, consider the following listing:

Potential source of impact	Water quality constituent	
	Enrichment factor >500	Enrichment factor 50 - 500
Retort water	Carbonate	Conductivity
	Ammonia	Alkalinity
	Phosphate	Chloride
	TOC (or DOC)	Bicarbonate

(continued)

TABLE 10-10. RELATIVE LIKELIHOOD OF DETECTION OF MOBILITY FROM VARIOUS SOURCES TO UPPER AND LOWER AQUIFERS AND SPRINGS BASED ON ESTIMATED ENRICHMENT FACTORS

Constituent	Lower to Upper Aquifer	Lower Aquifer to springs	In-situ leachate to Upper Aquifer	In-situ leachate to Lower Aquifer	Retort water to Upper Aquifer	Retort water to Lower Aquifer
General water quality measures						
Conductivity	---	---	2	3	2	3
Total dissolved solids	---	---	2	3	3	---
Alkalinity	---	---	---	---	2	3
Major inorganic ions						
Calcium	---	---	2	3	---	---
Magnesium	---	---	2	2	---	3
Potassium	3	3	2	---	3	---
Sodium	3	3	2	3	3	---
Chloride	---	---	2	2	2	3
Sulfate	---	---	2	1	---	3
Fluoride	---	3	3	---	---	---
Bicarbonate	---	---	---	---	2	---
Carbonate	---	---	1	2	1	1
Ammonia	3	3	---	---	1	1
Nitrate	---	---	---	---	2	2
Phosphate	---	---	---	---	1	1
Silica	---	---	---	---	---	3
Organics						
Total organic carbon	---	---	1	2	1	1
Phenolics	3	3	---	---	---	---
Kjeldahl nitrogen	---	---	---	---	1	---
Cyanide	---	---	---	---	2	2

(continued)

TABLE 10-10 (continued)

Constituent	Lower to Upper Aquifer	Lower Aquifer to springs	In-situ leachate to Upper Aquifer	In-situ leachate to Lower Aquifer	Retort water to Upper Aquifer	Retort water to Lower Aquifer
Sulfur species						
Total sulfur	---	---	---	---	3	2
Thiosulfate	---	---	---	---	1	1
Tetrathionate	---	---	---	---	2	2
Thiocyanate	---	---	---	---	1	1
Trace elements						
Arsenic	---	---	3	3	1	1
Barium	---	3	---	---	---	---
Boron	3	2	3	---	---	---
Bromide	3	3	---	---	3	---
Chromium	---	---	---	2	2	3
Cobalt	---	---	---	---	2	2
Iron	---	---	---	---	3	2
Lead	---	---	---	---	3	3
Mercury	---	---	---	---	1	1
Molybdenum	---	---	1	1	3	3
Nickel	---	---	3	2	3	2
Selenium	---	---	2	2	2	2
Titanium	---	---	---	---	3	3
Uranium	---	---	---	---	2	2
Vanadium	---	---	3	---	1	1
Zinc	---	---	3	3	3	3
Radiological						
Gross beta	---	---	---	---	3	---

[a] Enrichment factor (EF) categories: 1 = high likelihood of detection (EF = >500); 2 = moderate likelihood (EF = 50 to 500); relatively low likelihood (EF = 10 to 50).

Potential source of impact	Water quality constituent	
	Enrichment factor >500	Enrichment factor 50 - 500
Retort water (continued)		
	Kjeldahl N	Nitrate
	Thiosulfate	Cyanide
	Thiocyanate	Tetrathionate
	Arsenic	Chromium
	Mercury	Cobalt
	Vanadium	Selenium
		Uranium
In-situ spent shale leachate	Carbonate	Conductivity
	TOC (or DOC)	TDS
	Molybdenum	Calcium
		Magnesium
		Potassium
		Sodium
		Chloride
		Sulfate
		Selenium

Examination of this listing indicates that the following constituents may be unique indicators of impact of retort water or spent shale leachate on the Upper Aquifer. A unique indicator is one which is in the above listing for one source, but not for the other:

Possible unique indicators	
Retort water	In situ spent shale leachate
Alkalinity	TDS
Bicarbonate	Calcium
Ammonia	Magnesium
Phosphate	Potassium
Nitrate	Sodium
Kjeldahl N	Sulfate
Thiosulfate	Molybdenum

(continued)

Possible unique indicators	
Retort water	In situ spent shale leachate
Thiocyanate	
Tetrathionate	
Cyanide	
Arsenic	
Chromium	
Cobalt	
Mercury	
Uranium	
Vanadium	

Following the same procedure for consideration of monitoring in the Lower Aquifer, the following listing was extracted from Table 10-10.

	Water quality constituent	
Potential source of impact	Enrichment factor >500	Enrichment factor 50 - 500
Retort water	Carbonate	Nitrate
	Ammonia	Cyanide
	Phosphate	Total sulfur
	TOC	Tetrathionate
	Thiosulfate	Cobalt
	Thiocyanate	Iron
	Arsenic	Nickel
	Mecury	Selenium
	Vanadium	Uranium
In-situ spent shale leachate	Molybdenum	Chloride
		Carbonate
		TOC
		Chromium
		Nickel
		Selenium

Possible unique indicators were then identified from this listing:

Possible unique indicators	
Retort water	In-situ spent shale leachate
Ammonia	Sulfate
Phosphate	Magnesium
Nitrate	Chloride
Tetrathionate	Chromium
Thiosulfate	Molybdenum
Thiocyanate	
Arsenic	
Cobalt	
Iron	
Mercury	
Uranium	
Vanadium	

Indicator Constituents--

In addition to those water quality parameters for which baseline values have been established, additional species have been measured on a random basis in oil shale effluents. These species will be discussed in this subsection.

Inorganic species--Data presented earlier suggest that those trace elements forming stable, soluble anions under basic, oxidizing conditions are most likely to be enriched in leachates from a spent in-situ retort. It is thus interesting to speculate whether additional elements not discussed in Section 7 or above may behave similarly. Other trace elements which form anions under basic, oxidizing conditions include Te, Sb, Bi, Po, W, Re, and I, and their monitoring may, therefore, prove valuable. However, a more complete investigation of the geochemistry of these species is beyond the scope of this report and their potential mobility remains speculative.

Species such as SCN^-, $S_2O_3^=$, and $S_4O_6^=$ are normally not detectable in groundwaters and should, therefore, form excellent indicators of groundwater contamination. Since background concentrations of these species have not been measured, enrichment factors (Table 10-6) were calculated using estimated detection limits as background concentrations, based on the assumption that their concentrations were less than the detectable limit. The enrichment factors shown in Table 10-6 for these species recommend them as possible tracers of groundwater contamination, especially if even lower detection limits can be achieved.

Organic species The enrichment factors for TOC (or DOC) for both leachates and retort waters suggest organic matter as a valuable indicator. However, the baseline organic content of groundwaters actually varies widely;

Leenheer and Huffman (1976), for example, indicate levels of DOC of 30,700 mg/l for trona water collected near Eden, Wyoming. Few measurements in the Piceance Basin have been greater than about 10 mg/l. Leachates from raw shale may contain more organic acids than leachates from spent shale.

For these reasons, individual organic compounds (or compound classes) which are absent in natural groundwaters, but which are produced by the retorting process, should prove to be more sensitive probes of groundwater movement. For this reason, organic (DOC) fractionation methods, such as those described by Leenheer and Huffman (1976) may provide a set of useful indicators for monitoring.

One such type of organic compound could be aromatic acids, which are enriched in leachate from spent shale compared to raw shale. In addition, the smaller (lower molecular weight) aromatic acids should be highly soluble in the basic conditions expected and should, therefore, follow water movement closely. The larger acids, although ionized, could be more readily sorbed and, therefore, migrate less slowly.

Polynuclear aromatic hydrocarbons, which are products of combustion, may also increase during combustion.

Another likely organic tracer would be in hydrophilic bases. Much interest has focused on such compounds lately because of their biological activity and unusually large occurrence in oil shale products. Fruchter et al. (1977), for example, have found that indoles, substituted pyridines, quinolines, and acridines are highly enriched in shale oil as compared to coal-derived syncrude. Sievers and Denny (1978) have also detected numerous organic bases, many of which could not be readily identified, in retort waters. To the extent that such organic bases are retained by groundwaters, they should provide sensitive and unusual indicators of groundwater contamination.

Stable Isotopes--

It is well established that variations in isotopic abundances--especially for the light elements--occur naturally through such processes as diffusion, evaporation, dissolution, and chemical reaction. For example, ^{13}C is about 3 percent more abundant in ocean bicarbonate than in terrestrial petroleum (Roboz, 1968).

Similar variations in the isotopic ratios of other light elements, such as H, N, O and S, suggest this measurement as a probe for studying the migration of groundwater. As an example, suppose the $^{2}H/^{1}H$ ratio is slightly higher in kerogen than in natural groundwater. Water produced by combusting kerogen will thus be labeled with a higher $^{2}H/^{1}H$ ratio and could be distinguished from natural groundwater. Similar considerations to natural and combustion-produced NH_4^+, $CO_3^=$, and $SO_4^=$.

The variation in stable isotope abundances is normally reported as parts per thousand variation from a standard:

$$\delta = \frac{(I_2/I_1)_{\text{sample}} - (I_2/I_1)_{\text{standard}}}{(I_2/I_1)_{\text{standard}}}$$

where I_2 and I_1 refer to the minor and major isotope, respectively.

Variations in isotope ratios are measured almost exclusively by mass spectrometry. Although any mass spectrometer is capable of measuring isotope ratios, the measurement of naturally occurring variations requires highly specialized instruments. Indeed, many isotope ratio mass spectrometers are dedicated to a single element. Consequently, such instruments are found almost exclusively in research laboratories and are numerically absent from commercial laboratories.

Isotope ratio mass spectrometers are characterized by dual detector systems which are designed to collect both isotopes simultaneously, thereby minimizing errors due to ion current instability. Detector electronics are specifically designed to yield the isotope ratio directly, and ion sources typically include a means of switching rapidly between the sample and a standard of known isotopic composition. The precision with which δ may be measured in a routine matter is about 1 mil for H and 0.1 mil for C, O, and N. The precision of δ is typically limited by isotope fractionation which occurs during sample preparation and introduction into the mass spectrometer.

Although studies of isotope ratios in the Green River Formation have not been found in the literature, other relevant investigations deserve mention. Friedman et al. (1964), for example, discuss the natural variations of deuterium in the hydrologic cycle, including the theory of the fractionation processes which occur during evaporation, transport, and deposition. They also report the results of over 1000 determinations of ${}^{2}H$ in waters of North America. Dansgaard (1964) also discusses both the theory and the measurements of ${}^{2}H$ and ${}^{18}O$ in precipitation.

Holt et al. (1972) and Jensen and Nakai (1961) both discuss natural variations of ${}^{34}S$ in environmental samples. Holt et al. (1972) observed perturbations of $\delta^{34}S$ in surface waters due to rainfall, earth-surface disturbances, and effluents from sewage treatment plants.

N isotopic ratios have been studied widely, principally as a means of identifying pollutant sources and characterizing the atmospheric N cycle (Moore, 1977; Moore, 1974; Hoering and Moore, 1958; Wada et al., 1975). Naturally occurring values of $\delta^{15}N$ ranging from -15 to +25 have been observed.

Possible problems which may be encountered in the application of the stable isotope technique to the Green River Formation include lack of background data, insufficient difference in δ for natural and contaminated groundwater, and exchange reactions such as the following:

$${}^{1}H_{2}HO + {}^{1}HCO_3^- \rightarrow {}^{1}H_2O + {}^{2}HCO_3$$

$$H_2{}^{18}O + HC^{16}O_3^- \rightarrow H_2{}^{16}O + HC^{18}O^{16}O_2^-$$

Thus, to the extent that carbonates and bicarbonates exchange with, or precipitate as solid materials, the isotopic composition of certain elements may be altered.

Sampling and Sample Preservation

Sampling and sample preservation can be a major factor affecting the cost and effectiveness of a project. In his review of sample preservation and holding times, Carter (1979) addresses this problem directly and provides experimentally substantiated holding times for various water quality parameters.

Table 10-11 compares the holding times experimentally established by Carter for a variety of industrial waste waters with the holding times recommended in the EPA handbook, Methods for Chemical Analysis of Water and Wastes (U.S. EPA 1974). Table 10-11 also lists the preservatives recommended by Carter, which are normally, but not always, recommended by the EPA handbook.

The holding times recommended in the EPA handbook have caused considerable consternation and may have gained unwarranted credence. It is noteworthy that the experimentally established holding times shown in Table 10-11, column 3, are normally considerably longer than those recommended by the EPA handbook, but that holding times for Hg and pH are actually shorter. Thus, for industrial effluents, strict adherence to the EPA recommended holding times would result in dramatically increased cost as well as perhaps compromised data on pH and Hg.

It is thus clear that holding times recommended in the literature may be neither sufficient nor necessary for the purposes of monitoring groundwater in the Piceance Creek Basin area. Although Carter's data suggest considerably longer holding periods, it must be remembered that he dealt principally with industrial effluents which had elevated contaminant levels. For example, groundwaters which are exposed in-situ to partial pressures of CO_2 or H_2S which are elevated over atmospheric partial pressures of these gases may lose HCO_3^- and HS^- rapidly upon standing. It is recommended that, especially for crucial parameters, holding times be established experimentally for the waters under study. This could be done, for example, by preparing sealed vials containing known levels of contaminants, the contents of which could be added to duplicate samples in the field. Recovery in the laboratory of said additions would then indicate adequate preservation.

The preservation of aqueous effluents from oil shale retorting operations has been discussed briefly in the literature. For example, Felix et al. (1977) used high-pressure liquid chromatography to show that the organic species in retort waters underwent changes when stored at 37°C for 6 weeks, presumably because of microbial action. The individual organic species were not identified. Probably the most well known stability studies have been performed on the "Omega 9" retort water produced at the Rock Springs Site 9. Farrier et al. (1977) described this water and found that cooling to 4°C was the only effective method of inhibiting bacterial growth. Fox et al.

TABLE 10-11. EPA RECOMMENDED HOLDING TIMES COMPARED TO EXPERIMENTALLY ESTABLISHED HOLDING TIMES (Carter, 1979).

Measurement	Preservative	NPDES Holding Time	EPA Recommended[a] Holding Time
Alkalinity	4°C	2 wks	24 hrs
BOD	4°C	48 hrs	6 hrs
Bromide	None required	4 wks	24 hrs
COD	4°C, H_2SO_4 to pH < 2	4 wks	7 days
Chloride	None required	4 wks	7 days
Cyanides	4°C, NaOH to pH < 12	2 wks	24 hrs
Fluoride	None required	4 wks	7 days
Hardness	NHO_3 to pH < 2	6 mos	7 days
Iodide	Store in dark	4 wks	24 hrs
Mercury	0.05% $K_2Cr_2O_7$, HNO_3 to pH < 2	4 wks	38 days
Nitrogen			
Ammonia	4°C, H_2SO_4 to pH < 2	4 wks	24 hrs
Kjeldahl	4°C, H_2SO_4 to pH < 2	4 wks	24 hrs
Nitrate + Nitrite	4°C, H_2SO_4 to pH < 2	4 wks	24 hrs
Nitrite	4°C 4°C, 800 mg/l $HgCl_2$	24 hrs 7 days	24 hrs
Oil and grease	4°C, H_2SO_4 to pH < 2	4 wks	24 hrs
Organic carbon	4°C, H_2SO_4 to pH < 2	4 wks	24 hrs
pH	4°C	1 hr[b]	6 hrs
Phenolics	4°C, H_2SO_4 to pH < 2	4 wks	24 hrs
Phosphorus			
Orthophosphate, dissolved	4°C 4°C, 800 mg/l $HgCl_2$	24 hrs 7 days	24 hrs
Hydrolyzale	4°C 4°C, 800 mg/l $HgCl_2$	24 hrs 7 days	24 hrs
Total	4°C, H_2SO_4 to pH < 2	4 wks	24 hrs
Total, dissolved	4°C, H_2SO_4 to pH < 2	4 wks	24 hrs
Residual chlorine	4°C	1 hr	

(continued)

TABLE 10-11. (continued)

Measurement	Preservative	NPDES Holding Time	EPA Recommended[a] Holding Time
Residue			
Filterable	4°C	2 wks	7 days
Nonfilterable	4°C	1 wk	7 days
Total	4°C	2 wks	7 days
Silica	4°C	4 wks	7 days
Specific conductance	4°C	4 wks	24 hrs
Sulfate	4°C	4 wks	7 days
Sulfide	4°C, 2 ml zinc acetate	1 wk	24 hrs
Turbidity	4°C	24 hrs	7 days

[a] From EPA Methods for Chemical Analysis of Water and Wastes (U.S. EPA 1974).

[b] For accuracy of 0.2 pH units, 2 weeks holding time otherwise.

(1978a) also showed that up to 100 percent of the Hg was removed by bacterial action from retort waters produced at the Laramie simulated in-situ retort unless the samples were stored promptly at 4°C.

General references describing sampling procedures are available from the U.S. Geological Survey and U.S. Environmental Protection Agency (see, for example, Brown et al., 1970; U.S. EPA, 1976; and U.S. EPA, 1977). These should be readily available and will not be discussed here.

Chemical Analysis and Costs

This discussion is meant to aid the reader in the efficient selection of analytical techniques suitable for monitoring groundwater movement. Both survey and element-specific techniques are discussed.

Trace Elements--

The most common techniques which are used for trace element analysis are instrumental neutron activation analysis (INAA), inductively coupled plasma emission spectroscopy (ICP), spark source mass spectroscopy (SSMS), and atomic spectroscopy with its various modifications (AA). Each technique has strengths and weaknesses which should be recognized.

Table 10-12 compares these techniques on the basis of their abilities to detect trace levels of 44 elements. Although not shown on the table, the limit for SSMS is typically 1 μg/l for most elements. The detection limits for ICP were obtained from a recent review of an ICP spectrometer in use at a DOE synfuels laboratory, and were determined with artificial, multielement standards. The detection limits shown for a flamelsss (carbon rod) and flame AA were taken from the manufacturer's literature. The limits for INAA were for a routine survey available on a commercial basis. The working limits shown in the table are the lowest concentrations typically reported by a routine analytical services laboratory located in Denver. In this case, the working limits are typically several times the detection limit, since the method of choice in an analytical services laboratory is determined by regulatory requirement, economics, and ease of operation. It should be recognized that data in Table 10-12 represent a common basis for discussion, but that detection limits are often degraded in complex samples or improved by special pretreatment processes.

In addition to the detection limits, the precision and importance of interferences should be considered. ICP is relatively free of matrix interferences, but is subject to spectral interferences. For example, the DOE operators have reported poor accuracy for U, Co, As, and Cd on complex samples, presumably because of spectral interferences. AA has fewer spectral interferences, but special corrections may be needed for background or matrix interferences. The precision of AA or ICP spectrsocopy is typically ±10 percent when used by trained personnel. INAA is often considered a reference method for trace elements because of its relatively high precision at trace levels and freedom from matrix interferences. SSMS is typically subject to fewer interferences than either ICP or AA, but the routine precision for this technique is about ±40 percent, although precisions of ±3 percent have been reported in the literature using electrical detection under tightly controlled conditions. Since samples for SSMS must be dried onto a graphite substrate and placed in a vacuum, volatile elements such as Hg, S, and Se may be lost, especially under acidic conditions.

It is obvious that no single method is a panacea. INAA is attractive because of its detectability for the potential low-level indicators As, Sb, Se, Te, U, and V. SSMS is favored as a survey technique because it provides uniformly low detection levels and broad elemental coverage. The other methods listed in Table 10-12 are attractive as monitoring tools because of their adequate precision and detectability for many elements.

Organic Methods--

Common techniques which are available for the determination of trace organic species in complex mixtures include gas chromatography (GC), combined gas chromatography/mass spectroscopy (GC/MS), high-pressure liquid chromatography (HPLC), and thin-layer chromatography (TLC). Recent advances in controlling the variables in TLC are also giving rise to high-performance, thin-layer chromatography (HPTLC).

TABLE 10-12. COMPARISON OF ANALYTICAL TECHNIQUES FOR TRACE ELEMENT DETERMINATIONS[a]

Element	Detection limits				Working limit, Denver Laboratory		Colorado water quality standards cleanest classification
	ICP (µg/l)	Flameless AA (µg/l)	Flame AA (µg/l)	Instrumental Neutron Activation Analysis[b] (µg/l)	(µg/l)	Method[c]	(µg/l)
Ag	3	0.03	2	0.5	0.05	B	0.1
Al	3	2	20	100	100	A	100
As	16	15	100, 2[d]	0.5	2	B	50
B	15		2,000	NA	50	C	750
Ba	1	2	20	100	50	A	1,000
Be	1	0.2	0.7	NA	5	A	10
Bi	80	1.4	46	NA	500	A	---
Ca	2	0.06	2	1,000	50	A	---
Cd	15	0.02	0.7	0.10	2	A	0.4
Co	5	0.8	7	0.5	10	A	---
Cl	---	---	---	500	200	C	---
Cr	3	0.5	5	2	10	A	50
Cu	4	0.4	2	300	10	A	10
Ga	30	2	40	~70	---	---	---
Ge	20	---	100	NA	---	---	---
Fe	5	0.5	6	200	10	A	300
F	---	---	---	200	100	D	---

(continued)

TABLE 10-12 (continued)

Element	Detection limits				Working limit, Denver Laboratory		Colorado water quality standards cleanest classification
	ICP (µg/l)	Flameless AA (µg/l)	Flame AA (µg/l)	Instrumental Neutron Activation Analysis[b] (µg/l)	(µg/l)	Method[c]	(µg/l)
Hg	600	12	0.4[b]	0.5	0.02	[d]	0.05
K	50	0.2	2	300	100	A	---
Li	50	0.4	2	NA	5	A	---
Mg	1	0.006	0.2	5,000	50	A	125,000
Mn	5	0.04	2	20	5	A	50
Mo	7	0.6	30	3	5	B	---
Na	90	0.02	0.3	70	100	A	---
Nb	30	---	3,000	~25,000	---	---	---
Ni	9	1	8	NA	10	A	50
P	30	---	---	NA	100	C	---
Pb	20	0.3	15	NA	1	B	4
Sb	60	3	40	0.5	50	A	---
Se	20	6	250, 2[d]	1	5	B	10
Si	30	7	200	NA	1,000	C	---
Sn	12	1	30	80	500	A	---
Sr	10	0.8	2	2,000	10	A	---
S	---	---	---	NA	---	---	---

(continued)

TABLE 10-12

	Detection limits				Working limit, Denver Laboratory		Colorado water quality standards cleanest classification
Element	ICP (µg/l)	Flameless AA (µg/l)	Flame AA (µg/l)	Instrumental Neutron Activation Analysis[b] (µg/l)	(µg/l)	Method[c]	(µg/l)
Te	5	---	40	2	---	---	---
Ti	1	---	50	200	300	A	---
Th	---	---	---	0.2	---	---	---
Tl	200	0.6	13	NA	5	B	15
U	500	1,000	60,000	1	2	E	30
V	2	10	50	1	5	A	---
Zn	10	0.02	1	10	5	A	50
W	---	---	---	30	---	---	---
Br	---	---	---	1	---	---	---
I	---	---	---	30	---	---	---

[a] Detection limits correspond to approximately 20 times the background noise level. Working limits typically correspond to several times the background noise level and are based on a wide variety of groundwater and surface waters using equipment in a routine fashion.

[b] Note INAA not approved EPA method.

[c] A - flame atomic absorption; B - carbon rod atomic abosrption; C - colorimetric; D - electrode;
E - fluorometric.

[d] Vapor generation.

NA - not available under normal circumstances or very insensitive.

Standardized methods are not normally available for specific organic compounds since operating parameters are optimized for each substrate and analyte.

For the more tractable species, literature references may be found for similar substrates, although as a general rule a significant effort will be required for implementing, adapting, and "debugging" methods for groundwaters in the oil shale area. Organic bases are a particular problem since they readily decompose and since analytical methods are poorly developed.

Instrumentation should include a GC, GC/MS, and HPLC as a minimum, along with other standard analytical equipment. The GC/MS should be capable of operating with capillary columns and be capable of peak switching and single ion monitoring. A specific nitrogen detector on the GC should be considered essential for the determination of organic bases (Sievers and Denny, 1978).

Nonspecific separation schemes are also available for classifying the types of organic compounds in water (Hamersma et al., 1976; Leenheer and Huffman, 1976). Such schemes can provide a first warning of the groundwater changes and can indicate otherwise unsuspected changes. The procedures by Leenheer and Huffman may be of special interest since it was originally conceived as an aid in understanding the movement of organic materials in groundwaters. The procedure operates by separating hydrophilic and hydrophobic acidic, basic, and neutral compounds based on their adsorptive characteristics on artificial resins. In this scheme, the hydrophilic fractions should be most mobile in groundwater, while the hydrophobic fractions should most readily be retained by sorptive clays and minerals.

Other Inorganic Species--

For a wide variety of commonly occurring inorganic species, standard methods have been developed and tested which are reliable when applied to typical surface waters or groundwaters and which can be performed with a minimum of equipment (U.S. EPA, 1974; American Public Health Association, 1976; U.S. Geological Survey, 1970), Although standard methods must not be applied blindly to oil shale waste waters (or to other waste waters), it is believed that many standard methods can be modified slightly in order to produce more reliable results. In any case, a carefully designed quality assurance program is highly recommended.

This subsection first discusses several representative standard analytical procedures, analytical problems which occur, and possible solutions. A discussion of possible additional procedures which could be used to better or more efficiently analyze oil shale waste waters then follows.

Total suspended and dissolved solids--Normally these are determined by drying an aliquot of water at 103° to 105°C. In retort waters, this may cause the loss of ammonium carbonate and result in an artificially low result. A possible solution is evaporation at a different pressure and temperature to more selectively remove the water, or complete evaporation of ammonium carbonate, which is then determined separately.

Alkalinity--Normally, alkalinity is measured by titrating with dilute acid. Results are typically interpreted as total bicarbonate and carbonate. In retort waters, dissolved ammonia and organic acids are also titrated so that the results should be interpreted as "total titratable base." Another method is to determine carbonate and bicarbonate by measuring total inorganic carbon in a TOC analyzer and adjusting the pH and ionic strength. Other options include acidification of the sample and determination of the evolved CO_2 titremetrically, colorimetrically, or by hydrogenation and the detection of methane.

Chloride--Chloride is often determined by the subsequent reactions in a continuous flow system:

$$2Cl^- + Hg(SCN)_2 \rightarrow HgCl_2 + 2SCN^-$$

$$SCN^- + Fe^{3+} \rightarrow Fe(SCN)_x$$

The colored ferric thiocyanite complex is then detected colorimetrically. In retort water, thiocyanate is thus detected as chloride. This problem should be removed by chemically oxidizing the thiocyanate prior to analysis. Alternatively, analyzing subsequent samples with and without the addition of $Hg(SCN)_2$ may provide a determination for both chloride and thiocyanate.

pH--pH electrodes are subject to fouling by oils. This common problem can be overcome by frequent standardization or a cross check with a series of pH indicators, which are certainly as accurate, if not as convenient.

Nitrate--Often nitrate is determined by the automated Cd reduction method. A common problem is the fouling of the Cd reduction column by organic materials. A possible solution is extraction of the organic material prior to analysis, or the use of an alternate reducing agent, such as hydrazine.

BOD--In our experience, the normal BOD determination is not reproducible unless acclimated seed is used.

Ammonia--Often ammonia is determined with a selective ion electrode (which is subject to fouling by organic materials). A likely solution is removal of the organic materials by extraction, by filtration with a hydrophilic filter, or by the use of macroreticular resins.

Other constituents--It is likely that similar problems and relatively straightforward solutions may exist for other assays, such as fluoride and sulfate. Such minor modifications may be simple and, indeed, are often practiced by the alert analytical chemist. There are, of course, requirements for entirely new or greatly improved analytical methods. Possible analytical schemes are discussed below as examples.

Determination of the complex mixture of sulfur and nitrogen species found in retort waters is an unresolved problem. In addition, S, $S_2O_3^{=}$, $S_4O_6^{=}$, $S_3O_6^{=}$, $SO_4^{=}$, SCN^-, and CN^- can interreact and thereby change their chemical form. SCN^- can further react with oxidizing agents, which might be used in water treatment, to form the highly toxic cyanogen chloride.

One approach which has been used (Stuber et al., in press) for this problem is the cyanolysis of the various sulfur oxides with selective catalysts (Kelly et al., 1969). The resulting SCN^- was detected colorimetrically as the ferric thiocyanate complex. However, it has not yet been shown that the catalysts are sufficiently selective or that they do not occur naturally in sufficient quantities in waste waters.

There are several possible approaches to this problem which would be considered:

- Ion chromatography
- The development of coloring agents specific for thiosulfate, thiocyanate, tetrathionate, etc.
- Polarographic techniques which distinguish between the various S and N species on differing oxidation potentials
- Surrogate tests.

The latter tests assume that speciation of the various forms of S and N is not essential. As an example, $S_2O_6^=$, $S_3O_6^=$, and $S_4O_6^=$ could be determined as a group using the cyanolysis procedure of Kelly et al. (1969).

An especially attractive technique for such complex waters is ion chromatography. Because it is a separatory technique, complex and selective reactions are not required. Ion chromatography holds the possibility of chromatographically determining cyanide, thiocyanate, sulfate, thiosulfate, trithionate, tetrathionate, sulfide, as well as phosphate, fluoride and nitrate, minutes after sample collection. Because ion chromatography detects ions nonselectively, the presence of unexpected peaks alerts the analysts to unknown ions. Thus, the analyst can often detect previously unexpected compounds.

At the other extreme are tests which would measure, for example, total sulfur in all forms. Such a technique could be used to alert the analysts to the need for a more detailed analysis of sulfur species.

Costs--

The following are estimates of current laboratory unit costs for chemical analyses, based on single sample submission:

Trace metals by AA using standard curves	$ 6.00/sample
Trace metals by AA using the method of standard additions	15.00/sample
SSMS	225.00/sample
INAA with multiple exposure and counting periods	225.00/sample
ICP	45.00/sample

(continued)

Po-210 by alpha spectroscopy	64.00/sample
Ion chromatrography	50.00/sample
GC scan using developed, but nonstandard methods	300.00/sample
GC/MS	450.00/sample

Most metals measured by AA can be quantified using standard curves rather than standard additions. Exceptions are As and Se. It is recommended that most other trace elements be analyzed by standard additions at least once when dealing with unusual waters.

The prices listed above have been based on previous price quotations and current price lists, as well as simple estimates by contributors to this study.

It must be realized that these prices reflect methods which are already developed. Implementation of new methods must constitute a separate cost which would precede the actual analyses.

Data Analysis and Presentation

Data Analysis--

Data analysis procedures include (1) checks on data validity, and (2) methods for presenting data for interpretation for environmental description or control purposes. Data checking procedures include:

- Cation-anion balance
- TDS-conductivity comparison
- Conductivity-ion comparison (meq/l)
- Diluted-conductance method.

The cation-anion balance check involves considering the theoretical equivalence of the sum of the cations [expressed in milliequivalents per liter (meq/l)] and the sum of the anions (in meq/l). Because of variations in analysis which may be unavoidable, exact equivalence is seldom achieved. In general, the inequality observed can be expected to increase as the total ionic concentration increases. When using this method, it is assumed that analyses of all significant ions have been included and that the nature of the ionic species is known. In addition, it should be noted that compensating analytical errors can fortuitously produce a close ion balance. Hence, a combination of quality control (e.g., replicate analyses, use of standard references, spiked samples, etc.) and data checking procedures should be employed.

For other analysis checks, samples can be evaporated to dryness at 180°C and the weight compared to the total solids determined by calculation. This check is approximate because losses may occur during drying by volatilization and other factors may cause interference (Brown, Skougstad, and Fishman, 1970). Another recommended check on analyses involves multiplying specific conductance (μmhos/cm) by a factor ranging from 0.55 to 0.75. The product should approximately equal total dissolved solids, in mg/l, for water samples with TDS below 2000 to 3000 mg/l. Also, the specific conductance divided by 100 should approximately equal the meq/l of anions or cations. This relationship is useful in deciding on which sum, cations or anions, is in error. A more refined method for checking TDS by the electrical conductivity relationships, called the diluted-conductance method, may also be employed.

Proper design of the monitoring program with regard to selection of monitoring sites, sampling frequency and analytical methods, and implementation of quality control measures will alleviate such data interpretation problems. Good monitoring design can deal effectively with sources of data variability, such as operational variability of field instrumentations and errors in calculations or analysis.

Other significant sources of data variability are events such as in-plant spills, poor in-plant housekeeping practices, temporary process or control equipment failure or modification, and other in-plant events. These events may be entirely random (e.g., spills) or somewhat cyclic (e.g., equipment maintenance) in nature. Effectively dealing with these sources of data variability requires liaison with facility operators. Ideally, this communication should be of two types, namely to assure that (1) monitoring personnel have adequate knowledge of facility operations (and deviations), and (2) that plant developers have access to monitoring data and the evaluations made of that data. Such intercommunication can enhance data interpretation efforts.

Data Presentation--

Data presentation and interpretation are key aspects of monitoring for environmental detection and control. Several methods are available for organization and presentation of water quality data. These include tabulation and graphical tabulation of appropriate water quality criteria or standards, providing a format for screening data and identifying important sites or pollutant constituents. Ionic concentrations can be expressed as milligrams per liter or milliequivalents per liter. Other water quality measures may be segmented into contributing components, such as total and noncarbonate hardness or phenolphthalein and methyl orange alkalinity.

Graphic representations of analyses of the chemical quality of water are useful for display purposes, for comparing analyses, and for emphasizing similarities and differences. Graphs can also aid in detecting the mixing of waters of different composition and in identifying chemical processes occurring as water moves through the hydrologic regime of the monitoring area. A variety of graphic techniques is available; some of the more useful ones are described in the following paragraphs.

A widely used method of data presentation is the bar graph. On a bar graph, each sample analysis appears as a vertical bar whose total height is proportional to the total concentration of anions and cations, expressed in milliequivalents per liter. One-half of the bar represents cations and the other half anions. These segments are divided horizontally to show the concentrations of major ions or groups of closely related ions, which are shown by distinctive patterns. Variations include the addition of individual bar graphs to express levels of other water quality measures, such as hardness or un-ionized solutes such as silica.

Water quality data can also be plotted as a set of radiating vectors (Figure 10-5). Related methods of showing concentrations as linear vectors result in constructions of polygons. These approaches are useful in displaying changes in water quality as changes in, for example, the shape of these polygons. Trilinear diagrams are another useful method for representing and comparing water quality analyses (Figure 10-6).

Here, cations, expressed in percentage of total cations (as milliequivalents per liter), plot as a single point on the left triangle. Anions, similarly expressed as a percentage of total anions, appear as a point in the right triangle. These points are then projected into the central, diamond-shaped area parallel to the upper edges of the central area. This single point is thus uniquely related to the total ionic quality, and at this point a circle can be drawn with an area proportional to the total dissolved solids concentration. The trilinear diagram is a convenient way to distinguish similarities and differences among various water samples as waters with similar qualities will tend to plot together as groups. Also, simple mixtures of

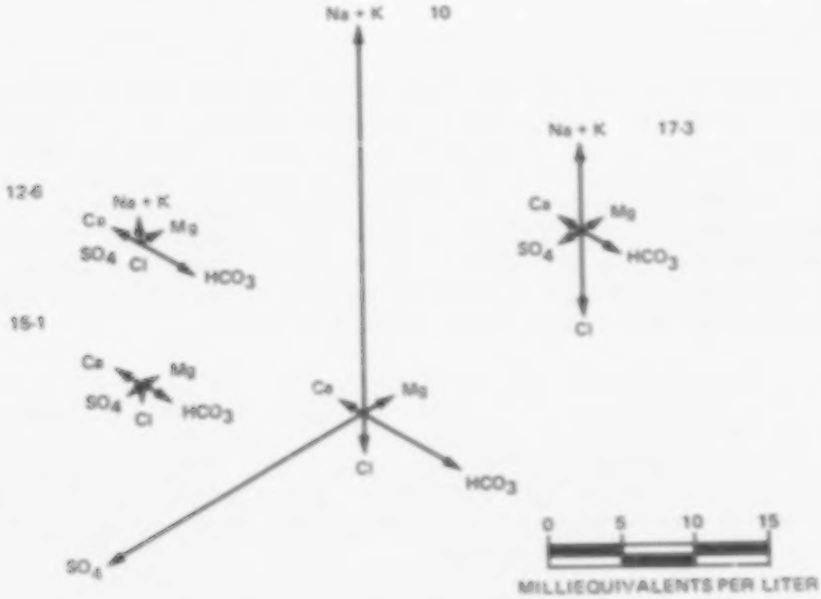

Figure 10-5. Water quality data display using vectors.

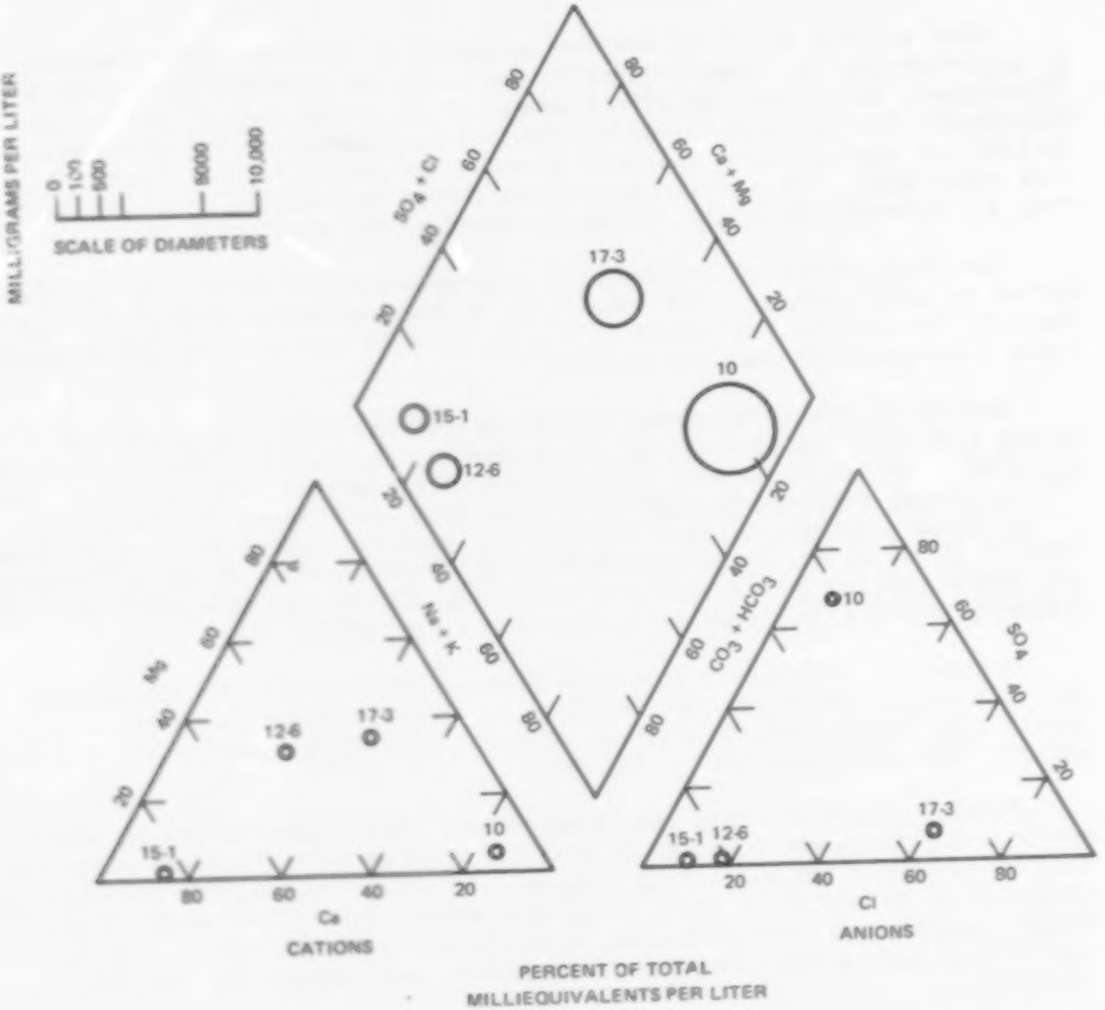

Figure 10-6. Trilinear diagram for displaying water quality data.

waters can be identified as the mixture data will plot at locations intermediate bewteen the mixture component waters.

Other graphic methods include time series plots, plots of variation in water quality constituents with distance or depth, area or cross-section plots of equal water quality lines, and plane maps. The choice of data presentation is determined by the goals of the monitoring program and the type of audience to which the data are to be presented. The goal of data presentation is to provide a clear portrayal of the data for evaluation of environmental quality.

Data Interpretation and Reporting--

Water quality data from monitoring should be analyzed and interpreted so as to define quality trends, identify new pollution problems or regions of improvement, and assess the effectiveness of pollution control activities. Assessments include such things as identifying segments of the groundwater systems not meeting water quality standards and projections of impact on various water uses. The monitoring program should incorporate pertinent data from all agencies and organizations involved in the monitoring region.

The final result of a monitoring program organized in an area is information on water quality. The final task of the monitoring program is to disseminate the information gained in usable forms to the agencies and organizations concerned with such information.

Monitoring should be summarized in appropriate forms for convenient study before wide distribution outside of the monitoring agency. This may involve preparation of tables showing averages and/or changes in water quality. Similarly, graphs prepared to readily display long-term trends may be helpful, as described previously. Maps showing, for example, locations of major known sources of pollution, areal distribution of concentrations of key pollutants, and regions having groundwater with qualities not meeting some water quality criterion can also be shown to be both useful and effective.

Monitoring information should be distributed regularly to appropriate public agencies--local, State, and Federal. Major industries in the area should also receive the material as well as cooperating agencies and organizations that contribute monitoring data.

Finally, the monitoring agency would have the responsibility to alert action and enforcement agencies of critical problems or situations which are discovered within the monitoring program. This may involve, for example, detection of hazardous or toxic pollutants which could affect water users. Prompt reporting of such instances is essential, as is following up with specialized monitoring efforts for documenting and controlling emergency situations.

SECTION 11

MONITORING DESIGN PROGRAM

INTRODUCTION

This report has summarized the results of the initial phase of a research program to address the groundwater quality impacts of MIS retort development. The goal of this research program is to develop recommendations for the monitoring of these impacts. The recommendations will provide a general evaluation and decision framework for design of monitoring programs for specific sites. In addition, procedures will be recommended for accomplishing the various evaluation tasks. The topics to be included under these recommendations are illustrated in Figure 11-1. Preliminary recommendations are provided in the "Summary and Design Recommendations" (p. vi and following).

Most of these topics (Figure 11-1) have been considered in some detail in the preceding sections of this report. Uncertainties and insufficient information exist to varying degrees in all of these areas. It should also be noted that data base needs for monitoring design may be very site-specific in many respects. The monitoring guidelines must be in the form of a design approach rather than a rigid set of specifications on, for example, number of monitoring wells, geometric configuration of wells, etc.

Based on the information presented in this report, the major issues relevant to monitoring design have been identified and are summarized in the following paragraphs. Areas of uncertainty are also identified. It is not the purpose of these discussions to provide preliminary general monitoring guidelines nor to specifically define monitoring plans for Tracts C-a and C-b. Data from Tracts C-a and C-b have been utilized in this study to illustrate current MIS development plans and environmental monitoring procedures being used for MIS development.

The purpose of the following discussions is to identify areas of study focus for Phase II of this research program. The final segment of this section presents a preliminary outline of Phase II studies aimed at addressing the data deficiencies and uncertainties identified during Phase I. The results of the Phase II studies will be to supplement the information base developed to date on this project and to provide a basis for developing a monitoring guideline document, such as illustrated in Figure 11-1. These recommendations will be based on assessment of anticipated effectiveness for obtaining needed monitoring information and on cost considerations.

- Chapter 1. Overview of Monitoring Design Strategy
- Chapter 2. Characteristics of MIS Retorts
  - -- MIS retort development and operation
  - -- Potential pollutants
- Chapter 3. Assessment of Hydrogeologic Framework and Water Quality
  - -- Coring and geophysical testing
  - -- Aquifer hydraulic characterization
  - -- Water quality characterization
- Chapter 4. Mobility Assessment
  - -- Mobility and attenuation mechanisms
  - -- Hydrogeologic factors
  - -- Flow net analysis
- Chapter 5. Monitoring Well Placement, Design and Operation
  - -- Hydrogeologic considerations (from Chapter 3)
  - -- Mobility considerations (from Chapter 4)
  - -- Water sample collection, preservation, and handling
  - -- Sampling frequency
- Chapter 6. Analysis
  - -- Selection of constituents
  - -- Analytical methods
  - -- Data analysis and presentation
- Chapter 7. Quality Assurance Programs

Figure 11-1. Preliminary outline--monitoring guideline document.

MONITORING DESIGN STRATEGY

The need for preplanning or design of monitoring programs is central to assuring the quality of monitoring data and the success of a monitoring strategy. A stepwise planning sequence (one iteration of which is presented in this report) which is directed toward design of source-oriented monitoring schemes is recommended. This direction is preferred over regional (or even tract-scale) design focus because it offers greater opportunity for early detection and possible control of groundwater quality impacts. With a source-specific orientation, monitoring programs are designed to indicate whether specific sources are or are not causing a problem. This is appreciably different than, as is the case with a regional focus in monitoring, an indication of whether or not the tract operation as a whole has already created a problem.

This source-specific approach has major implications with regard to the development of baseline data programs. The near-field (with regard to individual sources) hydrogeology and water quality, for example, should be the emphasis rather than the tract-wide or regional emphasis of the baseline programs developed to date. This near-field focus is particularly required in areas such as the Piceance Basin where the multilayered, fractured-rock aquifer systems create a very heterogeneous flow regime. Basin recommendations for baseline programs are:

- Emphasis on development of hydrogeology and water quality data within and in the immediate vicinity of proposed MIS retorts or retort fields
- Detailed coring, geophysical logging, and other sampling to define the three-dimensional character of permeable zones within retort fields
- Multiple completion of wells to isolate zones of widely variable hydraulic or water quality characteristics (well completion has been shown to have a very large effect on these data)
- Long-term aquifer tests within proposed retort fields (this will assist design of dewatering programs as well as groundwater monitoring programs).

In addition, the continual interplay between the engineering design of the mine and MIS retorts and the baseline study programs should be emphasized. Changes in facility design can be expected to result in altered data needed for the design of monitoring programs. The extent to which baseline data can be extrapolated to deal with changes in facility or operation design is finite, although clearly a matter of professional judgment.

Characteristics of MIS Retorts

MIS Retort Development and Operation--

The general features of the development and operation of MIS retorts are described in Section 2. Note that specific descriptions of Tract C-a and C-b developments are also presented as examples of commercial-scale MIS operations. It is anticipated that these MIS designs may change during the course of this research program as a result of new technology development of site-specific requirements on Tracts C-a and C-b. In addition, some uncertainty now exists with regard to access from within the mine for monitoring purposes.

Interaction with tract developers will be needed as this research project progresses in order to assure an adequate representation of this emerging industrial technology. Specific areas to be addressed include the following:

- Methods proposed to assist sealing or stabilizing abandoned retorts
- Flow, treatment, and disposition of retort waters

- Access to abandoned retorts themselves for sampling

- Access to retort zone for monitoring.

Potential Pollutants--

The general characteristics of potential pollutants from leaching of MIS spent shale and from MIS retort water are presented in Section 3. Most of these data utilize simulated in-situ spent shale samples; retort waters from various simulated in-situ, surface retorting, and true in-situ experiments (in Wyoming); and extrapolation from characterization of surface-retorted spent shale. These data offer a fairly good basic picture of what may be expected from MIS operations such as projected for Tracts C-a and C-b. Few data are available from MIS testing at Logan Wash by Occidental Oil Shale, Inc.

Basic uncertainties exist with regard to chemical characteristics of MIS spent shale leachate and retort water and the potential variability of these characteristics in time and space. These topics are closely related to the evaluations of leaching, mobility, and attenuation to be discussed later in this section.

The focus of characterization analysis should be one relevant for defining monitoring needs. Testing and analyses are needed to better identify chemical constituents which may be most appropriate for monitoring MIS retorts. Such constituents would indicate an impact on groundwater quality by:

- Appreciable change in concentration

- Presence of a constituent not normally associated with groundwaters

- Change in relative magnitude of various constituents (e.g., stable isotopes or organic fractions).

It would be advantageous to identify chemical constituents which would indicate the differential contribution of in-situ spent shale leachate and other residuals of retorting [e.g., retort water (shale oil)] remaining in the retort zone. Preliminary evaluations of these matters are presented in Section 10. This topic is also related to the selection of constituents, analytical methods, and data analysis segments of monitoring designs.

Assessment of Hydrogeologic Framework

A great volume of data on geologic characteristics, aquifer hydraulic parameters, and existing water quality has been developed on the Federal Oil Shale Lease Tracts. Data for the Colorado tracts presented in environmental baseline reports are summarized in Sections 5 and 6 of this report. Preliminary evaluation of these data has revealed the following areas for further evaluation:

- Use of coring and drilling information and geophysical testing associated with exploration activities in the design of hydrogeologic testing

- Use of selected methods for better defining the location and properties of fractured or solution-cavity intervals

- Use of the above data sets to identify well construction requirements (e.g., perforated zone) and monitoring design

- Aquifer test methods (including well location, pumping period, and data analysis)

- Influence of site-specific hydrogeology and well construction on water quality sampling, and water-level measurements, and aquifer testing data.

The initial three topics listed above are yet to be explored in detail in this study. The geophysical logging data have characteristically been segmented from the hydrologic data and were, for the most part, not reported in environmental baseline studies. Detailed interpretation of individual fracture zones as they may relate to groundwater flow, to potential pollutant mobility, and to influence on water quality samples has not been a large part of well design and monitoring programs.

In addition, recent testing related to development of dewatering-reinjection programs on Tract C-a has not been fully evaluated with regard to the application of these data to monitoring design. This effort will be undertaken during Phase II of this project.

Aquifer test methods employed on Tracts C-a and C-b are discussed and evaluated in Section 5. Areas of concern include:

- Location of test wells relative to MIS retort fields

- Selection of interval to be tested

- Duration of pumping

- Data analysis (e.g., relative to anisotropic conditions in the oil shale region).

Review of Tract C-a and C-b activities has provided some illustration relevant to these issues. For example, possible inconsistency exists in definition of the location of Upper and Lower Aquifers on Tract C-a. On the one hand, data show lack of aquifer interconnection across the Mahogany Zone. Well perforation sections were also selected using these data.

Several problems were also noted concerning aquifer tests conducted on the oil shale tracts:

- Test duration too short

- Nonconstant pumping rate not adequately accounted for in the test data analysis
- Improper correction of residual drawdown in pump-recover-pump approach on Tract C-b
- Improper analysis of recovery data
- Need correction for partial penetration
- More accurate water-level measurement methods needed.

Because of the heterogeneity of the hydrogeology of the oil shale region, aquifer tests should be conducted within proposed MIS retort fields. The duration of pumping may need to be very lengthy (e.g., more than 30 days) to adequately define boundary conditions (e.g., faults) in the test area. Data analysis methods appropriate for the anisotropic conditions, possible partially penetrating conditions, etc. must be selected to properly characterize groundwater flow conditions (see Section 5).

In general, programs for characterization of the hydrogeologic framework (1) should be focused on specific potential sources of impact (e.g., MIS retort fields) and (2) are probably best developed as a sequence of events of testing, data analysis, and progressing to further tests as indicated by the analysis. It would be advantageous to sample and to test the various permeable zones individually to better identify flow paths through proposed retort zones.

The limitations of well testing and sampling in heterogeneous hydrogeologic situations should also be recognized. Mine shaft and sublevel excavation activities offer an excellent opportunity to supplement information gained in pre-mine testing. Mapping of fractures and sampling water entering the mine, and collection of data during any in-mine drilling activities, should be integral parts of groundwater monitoring efforts.

Mobility Assessment

Evaluation of mobility and attenuation of potential pollutants in the subsurface is probably the most significant of the uncertainties existing in the development of groundwater quality monitoring programs. Some of this uncertainty is related to issues of the nature of potential pollutants and of the complex character of the hydrogeologic framework of the oil shale region. Discussions in Section 7 and Appendix A indicate that numerous simplistic models may be conceptualized. The actual predictive capacity of these models is subject to severe question because of the paucity of data available to validate the model results. However, from these simplistic analyses, several general conclusions can be drawn:

- Under certain hydrogeologic conditions (resulting from site-specific predevelopment conditions and modifications in the hydrogeologic framework (e.g., from dewatering and rubbling of in-situ retorts)), interaction between abandoned retorts and groundwater systems is likely

- Leaching of significant amounts of soluble materials is likely from some in-situ operations
- Appreciable decline in groundwater quality can result from in-situ oil shale development
- The impacts on groundwater quality may take several years to occur and have a very long duration (several decades or centuries).

The utility of modeling approaches can be enhanced by two methods:

- Enhanced characterization of the hydraulic properties and flow paths within and near the retort zone (see preceding discussion of assessing the hydrogeologic framework)
- Better characterization of leaching properties of MIS spent shale, including:
  - Mass of soluble materials leached (mass per unit mass spent shale)
  - Leaching rates (mass per pore volume)
  - Attenuation during flow through spent shale or natural geologic functions.

Such models may need to be parameterized in a very site-specific manner depending on the variability in spent shale characteristics as related to variations in raw shale or retorting conditions. The development of such descriptions of potential pollutant mobility is central to monitoring design.

Monitoring Well Placement, Design, and Operation

The placement and design of monitoring wells is defined by the design of the MIS operation, the site-specific hydrogeology, and by the potential mobility of constituents from the MIS retorts. Flow net analysis, including consideration of the anisotropic nature of the flow regime, is one key tool for locating monitor wells relative to the MIS retorts. The need for close proximity to the retorts was discussed earlier.

Hydrogeologic characterization efforts discussed earlier will assist in identifying aquifer intervals to be monitored. From a strict technical perspective, it is probably best to have separate completions in each aquifer zone producing appreciable amounts of water or exhibiting water quality which differs from adjacent zones. Obviously, some judgment would be required. It would be advantageous to drill and complete several monitor wells as part of one operation. Comparison of logs and other information from each hole should be undertaken to assure stratigraphic and hydrologic consistency between monitor wells. Development of such wells during baseline studies would greatly assist in defining intervals of perforation for any new wells required to monitor MIS operations.

The most representative groundwater quality samples are probably collected by puming. Other methods (such as bailing or swabbing) may be adequate provided that the well is properly cleaned out (e.g., several well volumes removed) prior to collection of samples for laboratory analysis.

Water Quality Analysis

Basic criteria for selection of constituents for monitoring are listed above under the discussion of characteristics of potential pollutants. In addition to these factors related to detection of potential pollutant mobility, other interpretive capability is also important. For example, constituents indicative of potential toxicity or other possible interference with water use would be good candidates for monitoring.

PHASE II STUDIES

Phase II of this research program will include a series of sampling, testing, and analysis tasks. The purposes of these tasks is to provide data to address the technical and economic issues raised in the preceding discussions. The task efforts defined will be coordinated to the extent feasible with other research efforts of EPA, DOE, USGS, and tract developers. Initially defined Phase II tasks are as follows:

- Task 1. Sampling Evaluations
    - -- Well sampling approaches
    - -- Well construction
    - -- Sample handling and preservation
    - -- Monitoring operational features
- Task 2. Hydrogeologic Characterization
    - -- Geophysical methods
    - -- Other testing procedures
    - -- Evaluate mine development phase data
- Task 3. Characterization of In Situ Sources
    - -- Chemical analysis
    - -- Leaching and mobility experiments
    - -- Selection of constituents for monitoring.

Task 1. Sampling Evaluations

Sample collection and handling play a central role in any monitoring program. During preliminary evaluations of the oil shale development, the following key items of concern have been raised. These items will be further assessed during Phase II with regard to their influence on groundwater quality data:

- Well sampling approaches (bailing versus pumping)
- Well construction (size, annular, sealing, casing material, packing, perforation, etc.)
- Sample handling and preservation (cooling).

Approaches for studying these items are provided in the following subtask descriptions.

Subtask 1a, Well Sampling Approaches--

During 1979 and 1980, the U.S. Geological Survey may be conducting a series of aquifer tests in the Piceance Basin. This testing program offers an excellent opportunity to evaluate alternative sampling procedures. Specifically, the following should be addressed:

- Compare water quality of samples bailed and samples pumped from same well
- Compare water quality of samples collected at various times during pumping.

The USGS will be collecting water samples at the end of several hours of pumping. To supplement these data, additional samples should be collected as follows:

- By bailing prior to pumping
- After 2 to 5 well volumes have been pumped from the well
- After 1 hour of pumping.

Thus, data would be collected to characterize a bailed sample (from the perforated interval); a very short-term pumping period sample (which may also approximate samples collected after first bailing or swabbing to flush out the well); a moderate pumping period (1-hour) sample, and a long-term pumping period sample (USGS sample).

For this program, the following is proposed as a minimum analytical program: major inorganic ions, TDS, pH, DOC, fluoride, arsenic, selenium, boron, and mercury. In order to minimize lab analysis as a source of variability, all samples should be analyzed by the USGS.

The sampling program outlined above will test sampling methods for deep aquifers in the Piceance Basin. In addition, pumped versus bailed samples from alluvial wells may be evaluated by taking advantage of the pump-sampling program utilized on Tract C-b. Similar to the deep aquifer testing program, samples should be collected as follows:

- Bailing prior to pumping
- After 2 to 5 well volumes have been pumped
- After an extended period of pumping.

Maximum use should be made of the data to be collected by Tract C-b personnel.

The same analytical program outlined above should be used for these alluvial well samples. To minimize sample variability, the samples should be analyzed at the same laboratory used by Tract C-b operators.

In addition to the samples collected for laboratory analysis, periodic field measurements of conductivity and pH should be made periodically during the pumping period.

This sampling program addresses the effectiveness of alternative sampling methods. Cost data (personnel, equipment, etc.) will also be compiled to provide an evaluation of cost effectiveness.

Subtask 1b, Well Construction--

Well construction can affect the nature of groundwater quality samples. Key elements of well construction include well size, annular seal, casing material, packing, well development, and selection of perforated interval. Evaluation of this latter element during Phase II will be closely coordinated with Task 2 assessments of hydrogeologic characterization approaches (described later).

Selection of well size is governed by the proposed use of a well and the methods selected for sample collection. For example, if only water level data are desired, then small-diameter (<2-inch) wells may be used. Depending on whether pumping, bailing, or other approaches are selected for collection of water quality samples, larger diameter wells will be needed. Assessment of well sizing will be integrated into the cost-effectiveness evaluation segment of Task 1a.

With regard to well sealing, packing, and developing, two activities are recommended for Phase II:

- Compile descriptions of well construction and development procedures which have been used in the Piceance Basin; Representative well construction methods will be identified
- Evaluate these various methods with regard to their potential influence on water quality data collected from the wells.

A literature search will be conducted to support an assessment of the influence of casing material on the results of water quality sampling. Consideration of costs and materials strength will be included in this evaluation.

To supplement these evaluations, data from Tract C-b wells collected before and after recompletion will be analyzed. Both water quality and water-level data sets will be compared to assist identification of the influence of well construction on the results of groundwater monitoring efforts.

Subtask 1c, Sampling Handling and Preservation--

The relative remoteness of the oil shale region can create some delay in receipt of samples at commercial analytical laboratories. In order to test the influence of these potential sample handling problems on the results of chemistry analysis, the following preliminary testing program is proposed:

- Split sample three ways and preserve each with EPA-recommended chemical preservatives
- Refrigerate or cool samples as recommended by EPA
- Ship samples (each split) to laboratory for analysis in following sequence:
  - First split sample as soon as possible after sampling (same day if possible)
  - Second split 5 days after sampling
  - Third split 12 days after sampling.

This is intended to simulate circumstances which can arise during field surveys: the initial split represents a "best" approach to shipment right after sampling. The second split represents the situation where samples collected during the week are shipped at the end of the week. The third split represents either a lengthy field survey (or perhaps one interrupted by weather or equipment problems) and shipment of samples at the end of two work weeks. The emphasis here will be on constituents with relatively short recommended holding times such as alkalinity, carbonate, bicarbonate, nitrate, sulfate, ammonia, and DOC.

An analytical program similar to that outlined under Task 1a should be adequate for this initial testing program. Sample collection should be coordinated with Task 1a sampling activities. A set of five samples, each split three ways, should be adequate for this analysis, and give an indication of the influence of shipment delay on the results of chemical analysis. After this preliminary testing, additional, more extensive testing of specific constituents will be recommended if the need is indicated.

Subtask 1d, Monitoring Operational Considerations--

Under this topic, several items were identified during the preliminary project evaluations:

- Physical access to spent retorts for monitoring
- Potential utility of in-situ sensors (e.g., salinity sensors) for monitoring within abandoned retorts.

To address the first item listed here, mine designs will be reviewed and discussion with tract developers will be pursued to address the following issues:

- Placement of wells within abandoned retorts
- Potential access through retort bulkheads
- Potential access using abandoned product recovery piping
- Potential utility of "long holes" (drilled adjacent to retorts for dewatering purposes).

The costs and effectiveness of these in-mine approaches will be compared to costs of drilling new monitor wells from the surface or from within the mine.

The evaluation of the use of salinity sensors for in-situ monitoring will be addressed during the above-outlined discussions with regard to physical access to the retort zone. The operation of such sensors in the abandoned retort environment will be evaluated as part of Subtask 3b.

Task 2. Hydrogeologic Characterization

The hydrogeologic characteristics of the oil shale region are quite variable. The design of a groundwater quality monitoring program for a given in-situ operation will be governed by the site-specific hydrogeologic features. Baseline monitoring and testing programs have focused largely on the general tract or regional features. The detailed features of the in-situ retort field areas are being better defined as a result of, for example, dewatering-reinjection testing and mine development on Tract C-a. The goal of Task 2 activities will be to (1) evaluate and recommend testing methods which are appropriate for hydrogeologic testing programs prior to mine development, and (2) identify and analyze data being collected or collectable during mine development which are applicable to defining monitoring program needs. Several subtasks have been identified for Task 2.

Subtask 2a, Geophysical Methods--

Section 10 of this report contains a summary of geophysical methods which may be appropriate for defining the hydrogeologic characteristics of in-situ development sites. During Task 2a, the following evaluations are to be performed:

- Reanalyze geophysical data from tract exploration phases (not included in environmental baseline reports) with regard to the utility of these approaches for examining porosity with retort fields

- Develop cost estimates for implementing the geophysical methods outlined in Section 10

- Rank alternative approaches relative to cost, potential effectiveness (i.e., producing needed information), and availability of the various geophysical tools in the oil shale region

- Identify methods which may be useful in existing core holes or wells to fill in data gaps for Tracts C-a and C-b in-situ retort fields; recommend testing program (perhaps for summer 1980) and identify costs.

Subtask 2b, Other Testing Procedures--

In addition to geophysical methods, other testing procedures exist which are useful for characterizing fractured rock/solution cavity aquifer systems such as are found in the oil shale region. Some of these are identified in Section 10. The characteristics which need to be defined by pumping, injection, or other testing procedures are:

- Hydraulic properties of different fractured intervals

- Characteristics of confining beds (leakance)

- Vertical head gradients

- Influence of faults as hydraulic barriers or pathways.

Aquifer testing conducted during the baseline programs has already been examined and is discussed earlier in this report. To supplement this evaluation, the following activities are recommended for Task 2b:

- Analyze subsequent testing associated with dewatering-reinjection program conducted on Tract C-a

- Develop cost estimates for alternative testing approaches for defining above-listed characteristics

- Rank these approaches relative to costs, potential effectiveness, and availability of appropriate testing equipment

- Identify methods which may be useful for testing of existing core holes or wells on Tracts C-a and C-b; recommend testing program (possibly for summer 1980) and identify costs.

Subtask 2c, Evaluate Mine Development Phase Data--

As mine access shafts and sublevels are developed, a perspective of the fractured rock system of the retort field can be gained which greatly supplements the data gained by the various well test and sensing procedures considered in Subtasks 2a and 2b. Such additional data can be gained by mapping of fractures encountered during mine development, observing relative amounts of water entering the mine in different zones and sampling the water quality of water entering the mine in different zones.

During Subtask 2c, such data collected by tract developers will be compiled to supplement the other data on the hydrogeology of the retort fields. Recommendations for additional data collection will be made as data needs are identified.

Task 3. Characterization of In-Situ Sources

The term "characterization" is used here in a broad sense and includes consideration of the following:

- Chemical characteristics of potential pollutants
- Leaching characteristics
- Selection of constituents for monitoring (including utility of tracers, enrichment factors, and stable isotopes)
- Evaluation of mobility/attenuation mechanisms.

To address these areas of importance (and deficiencies identified in preliminary evaluations) several subtasks have been identified.

Subtask 3a, Chemical Analysis of In-Situ Sources--

The focus here will be on evaluating the characteristics of in-situ spent shale, retort waters, and mine water. The initial element of this subtask is to obtain samples of, or data on, in-situ retorting byproducts. At present, Logan Wash is the most appropriate site for obtaining such samples since the retorting technology used at Logan Wash is that to be utilized on Tracts C-a and C-b. Beyond collection of samples of spent shale for leaching and mobility evaluations (Subtask 3b), the following are to be considered during Subtask 3a:

- Variability of spent shale relative to variations in raw shale from the interval retorted
- Presence of retort water or other product residues on in-situ spent shale
- Time variability of retort water quality and quantity during retorting.

Other data sources include other research programs (such as Laramie Energy Technology Center) and samples from the initial burn on Tract C-a (projected now for the spring of 1980).

Initial efforts on this subtask will focus on attempting to compile and evaluate data collected by Occidental Oil Shale, Inc., and LETC from Logan Wash. From this effort, additional sampling needs will be identified and a program developed for the initial Tract C-a retort.

Subtask 3b, Leaching and Mobility Experiments--

Experiments to evaluate leaching and mobility of in-situ potential pollutants should address the following issues:

- Mass of various chemical species leached
- Leaching rates
- Attenuation of leached products during flow through spent shale, raw shale, and other geologic materials.

Such experiments should approximate, to the extent reasonable, the long time frame and slow flow rates anticipated for leaching in the retort zone.

As indicated by discussions in Section 7, the mechanisms by which in-situ retorts may be interconnected with aquifers and may be filled and leached are unclear. Thus, any leaching simulation will be a rough approximation. However, several experimental design criteria are apparent:

- Contact time between leaching water and spent shale should be lengthy
- Natural waters should be utilized for the experiments.

A conceptual experimental design is outlined below:

- Pack a relatively large (e.g., 12-inch-diameter x 6-foot-long) column with spent shale
- Column should have ports of at least 1-foot increments for the following:

  -- Salinity sensors

  -- Open tubes for sample collection

  (The placement of salinity sensors is related to Task 1 testing as well as data collection)

- Flow through the column (bottom to top) should be set at rate of approximately one pore volume per month

- Column should be filled from the bottom.

Data collection will include collection of a sample at each sample port as the water reaches that level and weekly thereafter. The analysis program is outlined later under the Subtask 3c description.

Salinity sensors should be monitored at least daily and the results compared to small water samples collected and checked for electrical conductivity. The pH of these samples should also be measured at the time collected.

The experimental program outlined above should provide an indication of:

- The mass of soluble materials leached from in-situ spent shale (mass per unit mass spent shale)

- The leaching rate (mass per pore volume)

- The constituents which may be attenuated (e.g., sorbed or precipitated) during flow through an abandoned retort column.

In addition, the utility of in-situ salinity sensors will be evaluated (Subtask 1d) and the use of various constituents as tracers or indicator species will be assessed (Subtask 3c).

In an abandoned retort field (and assuming aquifer interconnection with the abandoned retorts and subsequent leaching) groundwater flow through in-situ spent shale may be followed by flow through raw shale and other materials of the Green River Formation and ultimately through materials of the Uinta Formation. To evaluate potential attenuation of leached constituents during flow through these materials, secondary columns containing these materials may be constructed to receive the effluent from the spent shale leaching column. Since flow in the Green River and Uinta Formations is through fractures, these secondary columns should be packed with relatively large pieces of these geologic materials to simulate the relatively small surface area available naturally for adsorption of other attenuation processes.

Other experiments such as those dealing with mobility of potential residues of shale oil or retort water in the spent shale would also be beneficial. Their feasibility is contingent upon availability of in-situ spent shale and analytical costs. Beaker or shaker leaching tests should also be considered as an alternative test procedure. Such laboratory-scale experiments will be coordinated with the activities of other oil shale research groups.

Subtask 3c, Selection of Constituents for Monitoring--

Selection of constituents for monitoring includes consideration of the following options:

- Constituents whose qualitative presence indicates groundwater quality impact (e.g., sulfur species, some organics)

- Constituents expected to change significantly if groundwater quality impacts occur (e.g., total dissolved solids, pH, certain trace elements)

- Constituents which may exhibit a relative change if impacts occur (e.g., stable isotopes).

The potential use of these approaches in selection of indicator chemical species is discussed in Section 10. These evaluations have indicated a number of chemical species which may be useful indicators. The leaching and mobility experiments (Subtask 3b) should be utilized to further assess the utility of the constituents identified in Section 10. The evaluation of the potential mobility of these indicator species should result in a better definition of constituents useful for detection and monitoring of groundwater quality impacts.

From the Section 10 evaluation of enrichment factors, the following constituents were identified as potentially unique indicators in the Upper Aquifer from leaching of spent shale:

TDS

Calcium

Magnesium

Potassium

Sodium

Sulfate

Molybdenum

Similarly, the following were identified for the Lower Aquifer:

Sulfate

Magnesium

Chloride

Chromium

Molybdenum

Other indicators (constituents not normally associated with natural groundwaters) identified were:

- Trace elements forming anions under basic, oxidizing conditions (Te, Sb, Bi, Po, W, Re, I)

- Sulfur species (SCN^-, $S_2O_3^{=}$, $S_4O_6^{=}$)

- Organics (aromatic acids, PAH, hydrophilic bases.

Constituents for this testing should be selected from these lists plus the constituents of interest identified under the Task 1a description.

This initial Subtask 3c evaluation will concentrate on the first two sets of constituents listed above. The assessment of stable isotope tracers will be extended with an evaluation of the availability and cost of analysis of the alternative constituents identified in Section 10. Depending on the results of this assessment, further testing of the feasibility of using stable isotopes as tracers will be recommended.

REFERENCES

American Public Health Association, *Standard Methods,* 19th Edition, Washington, D.C., 1976.

Amy, G.L., "Contamination of Groundwater by Organic Pollutants Leached from In Situ Spent Shale," Ph.D. dissertation, University of California, Berkeley, California, 1978.

Amy, G.L., and J.F. Thomas, "Factors that Influence the Leaching of Organic Material from In Situ Spent Shale," *Proceedings of Second Pacific Area Chemical Engineering Congress* (undated).

Amy, G.L., J.F. Thomas, and A.L. Hines, "Leaching of Organic Residuals from Simulated In Situ Retorted Oil Shale," preprints of Division of Fuel Chemistry, American Chemical Society (undated).

Bredehoeft, J.D., R.G. Wolff, W.S. Keys, and E. Shutter, "Hydraulic Fracturing to Determine the Regional In-Situ Stress Field, Piceance Basin, Colorado," *Bull. Geol. Soc. Am.,* Vol. 87, pp 250-258, 1976.

Brown, F., M.W. Skougstad, and M.J. Fishman, *Methods for the Collection and Analysis of Water Samples for Dissolved Minerals and Gases,* U.S. Geological Survey, 1970.

Carter, M.J., "Wastewater Sample Preservation Data for Twenty Common Water Quality Parameters," personal communication, 1979.

Cashion, W.B., *Geology and Fuel Resources of the Green River Formation, Southwestern Uinta Basin, Utah and Colorado,* U.S. Geological Survey Professional Paper 548, 1967.

C-b Shale Oil Venture, *Modifications to Detailed Development Plan,* Ashland Oil, Inc., and Occidental Oil Shale, Inc., February 1977a.

C-b Shale Oil Venture, *Environmental Baseline Program, November '74 - October '76,* Final Report, 1977b.

Chappel, W., "Trace Elements in Oil Shale," Environmental Trace Substances Research Program, University of Colorado, Progress Report, 1978.

Dansgaard, W., "Stable Isotopes in Precipitation," *Tellus,* Vol. 16, No. 33, 1964.

Davis, S.N., and R.J.M. DeWiest, Hydrogeology, John Wiley and Sons, Inc., New York, 1966.

Desborough, G.A., J.K. Pitman, and C. Huffman, Jr., "Concentration and Mineralogical Residence of Elements in Rich Oil Shales of the Green River Formation, Piceance Creek Basin, Colorado, and the Uinta Basin, Utah," Chem. Geology, Vol. 17, No. 13, 1976.

Everett, L.G., (ed.), Groundwater Quality Monitoring of Western Coal Strip Mining: Identification and Priority Ranking of Potential Pollution Sources, EPA-600/7-79-024, U.S. Environmental Protection Agency, January 1979.

Farrier, D.S., R.E. Poulson, Q.D. Skinner, and J.C. Adams, "Acquisition, Processing, and Storage for Environmental Research of Aqueous Effluents Derived from In Situ Oil Shale Processing," Proceedings Second Pacific Chemical Engineering Congress, 1977.

Felix, W.D., D.S. Farrier, and R.E. Poulson, "High Performance Liquid Chromatographic Characterization of Oil Shale Retort Waters," Proceedings Second Pacific Engineering Congress, 1977.

Ficke, F.J., J.B. Weeks, and F.A. Welder, Hydrologic Data from the Piceance Basin, Colorado, Colorado Water Resources Basic-Data Release No. 31, U.S. Geological Survey in cooperation with the Colorado Department of Natural Resources, Denver, Colorado, 1974.

Fox, J.P., D.S. Farrier, and R.E. Poulson, Chemical Characterization and Analytical Considerations for an In-Situ Oil Shale Process Water, LETC/RI-78/7, Laramie Energy Technology Center, Laramie, Wyoming, November 1978a.

Fox, J.P., R.D. McLaughlin, T.C. Bartke, J.J. Duvall, K.K. Mason, and R.E. Poulson, "Mercury Emissions from a Simulated In Situ Oil Shale Retort," 11th Annual Oil Shale Symposium Proceedings, Golden, Colorado, April 12-14, 1978b.

Friedman, I., A.C. Redfield, B. Schoen, and J. Harris, "The Variation of the Deuterium Content of Natural Waters in the Hydrologic Circuit," Reviews of Geophysics, Vol. 2, No. 177, 1964.

Fruchter, J.S., J.C. Laul, M.R. Peterson, P.W. Ryan, and M.E. Turner, "High Precision Trace Element and Organic Constituent Analysis of Oil Shale and Solvent-Refined Coal Materials," ACS New Orleans Meeting, Division of Petroleum Chemistry, Symposium on Analytical Chemistry of Tar Sands and Oil Shale, March 20-25, 1977.

Hamersma, J.W., S.L. Reynolds, and R.F. Maddalone, Level 1 Environmental Assessment, EPA-600/2-76-160a, U.S. Environmental Protection Agency, June 1976.

Hendricks, D.W., and J.C. Ward, "Environmental Analysis of an Oil-Shale Industry in the Upper Colorado Region," Oil Shale (T.F. Yen and G.V. Chilingarian, eds.), 1976.

Hendrickson, T.A. (ed.), Synthetic Fuels Data Handbook, Cameron Engineers, Inc., Denver, Colorado, 1975.

Hoering, T.C., and H.E. Moore, "The Isotopic Composition of the Nitrogen in Natural Gases and Associated Crude Oils," Geochemica et Cosmochemica Acta, Vol. 13, No. 225, 1958.

Holt, B.D., A.G. Engelkeneir, and A. Benters, "Variation of Sulfur Isotope Ratios in Samples of Water and Air Near Chicago," Env. Sci. & Tech., Vol. 6, pp 338-341, 1972.

Hubbard, A.B., "Method for Reclaiming Waste Water from Oil Shale Processing," American Chemical Society, Division of Fuel Chemistry, reprints Vol. 16, No. 1; referenced in K.D. Linstedt et al., 1976, Characterization and Treatment of Retort Water from In Situ Oil Shale Processing, Final Report PL61683, ERDA-LERC, 1976.

Jackson, L.E., R.E. Poulson, T.J. Spedding, T.E. Phillips, and H.B. Jensen, "Characteristics and Possible Roles of Various Waters Significant to In Situ Oil Shale Processing," Quarterly of Colorado School of Mines, Vol. 70, 1975.

Jensen, M.L., and N. Nakai, "Sources and Isotopic Composition of Atmospheric Sulfur," Science, Vol. 134, pp 2102-2104, 1961.

Kelly, D.P., L.A. Chambers, and P.A. Trudinger, "Cyanolysis and Spectrophotometric Estimation of Trithionate in Mixture with Thiosulfate and Tetrathionate," Anal. Chem., Vol. 41, p. 898, 1969.

Knutson, C.F., Project Rio Blanco: Evaluation of Possible Radioactivity Transport in Groundwater, CER Geonuclear Corporation, Las Vegas, Nevada, 1973.

Kruseman, G.P., and N.A. DeRidder, Analysis and Evaluation of Pumping Test Data, International Institute for Land Reclamation and Improvement, Netherlands, 1976.

Lawrence Berkeley Labs (LBL), "Diffuse Source Effects on In Situ Oil Shale Development on Water Quality," draft report, 1978.

Leenheer, J.A., and E.W.D. Huffman, Jr., "Classification of Organic Solutes in Water by Using Macroreticular Resins," Journal Research, U.S. Geological Survey, Vol. 4, No. 6, p. 737, 1976.

Margheim, G., "Water Pollution from Spent Oil Shale," Ph.D., Thesis, Colorado State University.

Moore, H., "Isotopic Measurement of Atmospheric Nitrogen Compounds," Tellus, Vol. 26, No. 167, 1974.

Moore, H., "The Isotopic Composition of Ammnonia, Nitrogen Dioxide and Nitrate in the Atmosphere," Atmos. Environ. II, No. 1239, 1977.

Parker, H.W., R.M. Bethea, N. Gunen, M.N. Gazdar, and J.C. Watts, "Interactions Between Ground Water and In Situ Retorted Shale," Proceedings Second Engineering Congress, 1977.

Pfeffer, F.M., Pollution Problems and Research Needs for an Oil Shale Industry, Environmental Protection Technology Series, U.S. Environmental Protection Agency, June 1974.

Poulson, R.E., J.W. Smith, N.B. Young, W.A. Robb, and T.J. Spedding, Minor Elements in Oil Shale and Oil Shale Products, LERC Report of Investigations 77/1, 1977.

RBOSP, Detailed Development Plan--Tract C-a, submitted to AOSS, March 1976.

RBOSP, Revised Detailed Development Plan, Tract C-a, Gulf Oil Corporation--Standard Oil Company (Indiana), May 1977a.

RBOSP, Final Environmental Baseline Report for Tract C-a and Vicinity, May 1977b.

Roboz, J., "Introduction to Mass Spectrometry," Interscience, New York, 1968.

Sievers, R.E., and D. Denny, Investigation of Trace Organic Compounds in Oil Shale Wastes, Progress Report, 1978.

Slawson, G.C. (ed.), Groundwater Quality Monitoring of Western Oil Shale Development: Identification and Priority Ranking of Potential Pollution Sources, EPA-600/7-79-023, U.S. Environmental Protection Agency, January 1979.

Slawson G.C., Groundwater Quality Monitoring of Western Oil Shale Development: Monitoring Program Development, General Electric--TEMPO Report GE78TMP-90, U.S. Environmental Protection Agency, in press, 1980.

Smith, J.W., W.A. Robb, and N.B. Young, "High Temperature Reactions of Oil Shale Minerals and Their Benefit to Oil Shale Processing In Place," 11th Annual Oil Shale Symposium Proceedings, Colorado School of Mines, April 1978.

Stuber, H.A., and J.A. Leenheer, "Fractionation of Organic Solutes in Oil Shale Retort Waters for Sorption Studies on Processed Shale," U.S. Geological Survey, paper presented at ACS Fuel Sciences Division Symposium, 1978.

Stuber, H.A., J.A. Leenheer, and D.S. Farrier, Inorganic Sulfur Species in Waste Waters from In Situ Oil Shale Processing, in press.

Tiratsou, E.N., Oilfields of the World (2nd Edition), Scientific Press, Ltd., Beaconsfield, England, 1976.

Todd, D.K., R.M. Tinlin, K.D. Schmidt, and L.G. Everett, Monitoring Groundwater Quality: Monitoring Methodology, EPA-600/4-76-076, U.S. Environmental Protection Agency, 1976.

U.S. Atomic Energy Commission, Environmental Statement: Rio Blanco Gas Stimulation Project, Rio Blanco County, Colorado, April 1972.

U.S. Environmental Protection Agency, Methods for Chemical Analysis of Water and Wastes, EPA-625/6-74-003, 1974.

U.S. Environmental Protection Agency, Handbook for Sampling and Sample Preservation of Water and Wastewater, EPA-600/4-76-049, 1976.

U.S. Environmental Protection Agency, Sampling of Water and Wastewater, EPA-600/4-77-039, 1977.

U.S. Geological Survey, "Methods for Collection and Analysis of Water Samples for Dissolved Minerals and Gases," Techniques of Water Resources Investigations of the U.S. Geological Survey, U.S. Government Printing Office, Washington, D.C., 1970.

Wada, E., T. Kadonga, and S. Matsuo, "^{15}N Abundance in Nitrogen of Naturally Occurring Substances and Global Assessment of Denitrification from Isotopic Viewpoint," Geochemical Journal, Vol. 9, No. 139, 1975.

Warner, D.L., Monitoring Disposal-Well Systems, EPA-680/4-74-008, U.S. Environmental Protection Agency, July 1975.

Weeks, J.B., and F.A. Welder, Hydrologic and Geophysical Data from the Piceance Basin, Colorado, Colorado Water Resources Basic-Data Release No. 35, U.S. Geological Survey in cooperation with the Colorado Department of Natural Resources, Denver, Colorado, 1974.

Weeks, J.B., G.H. Leavesley, F.A. Welder, and G.J. Saulnier, Jr., Simulated Effects of Oil Shale Development on the Hydrology of Piceance Basin, Colorado, U.S. Geological Survey Professional Paper 908, 1974.

Welder, F.A., and G.J. Saulnier, Jr., Geohydrologic Data from Twenty-Four Test Holes Drilled in the Piceance Basin, Rio Blanco County, Colorado, 1974-76, U.S. Geological Survey, Open-File Report 78-734, Lakewood, Colorado, September 1978.

APPENDIX A

CONCEPTUAL MODELS OF POTENTIAL POLLUTANT MOBILITY

Three conceptual models are described in the following summaries. These models provide a preliminary evaluation of the "state of knowledge" of quantitative prediction of the groundwater quality impacts of MIS development. This set of models is not intended to be complete.

CONCEPTUAL MODEL 1

The following scenario is taken from Amy (1978) and is provided here as an introduction to the potential groundwater impacts of abandoned in-situ retorts. This scenario is based on the concept of a two-aquifer hydrogeologic system with in-situ retorting of the Mahogany Zone between two aquifers (Figure A-1).

Prior to and during retorting, adjacent aquifers will be continuously dewatered in order to prevent groundwater from interfering with the retorting process. Upon completion of retorting, dewatering operations will eventually cease and groundwater will slowly migrate into abandoned retorts until steady-state flow conditions are eventually established. A likely pattern of groundwater flow through a retort is depicted in Figure A-2. The flow pattern described in Figure A-2 is highly idealized and assumes that (1) the confining shale layer is situated between two aquifers as in the Piceance Basin, (2) the retort completely penetrates the shale layer and thus establishes communication between adjacent aquifers, and (3) the head difference between the Upper and Lower Aquifers is sufficient to produce upward flow through the retort (as will occur in many parts of the Piceance Basin).

One potential scenario for the transport of leached contaminants is presented by Amy (1978) (Figure A-2). Groundwater from the Lower Aquifer migrates into an abandoned retort after dewatering operations have ceased and, eventually, steady-state flow conditions are established. Various organic contaminants may be leached from spent shale as groundwater flows upward through the retort. Subsequently, contaminated groundwater enters the Upper Aquifer and, in response to the existing gradient, flows toward a point of discharge, such as a well or the gaining reach of a stream.

As contaminated groundwater enters the Upper Aquifer, a certain degree of dilution will occur as it mixes with uncontaminated groundwater from the Upper Aquifer. As it flows through the Upper Aquifer, contaminated groundwater may also be improved in quality as a consequence of natural treatment

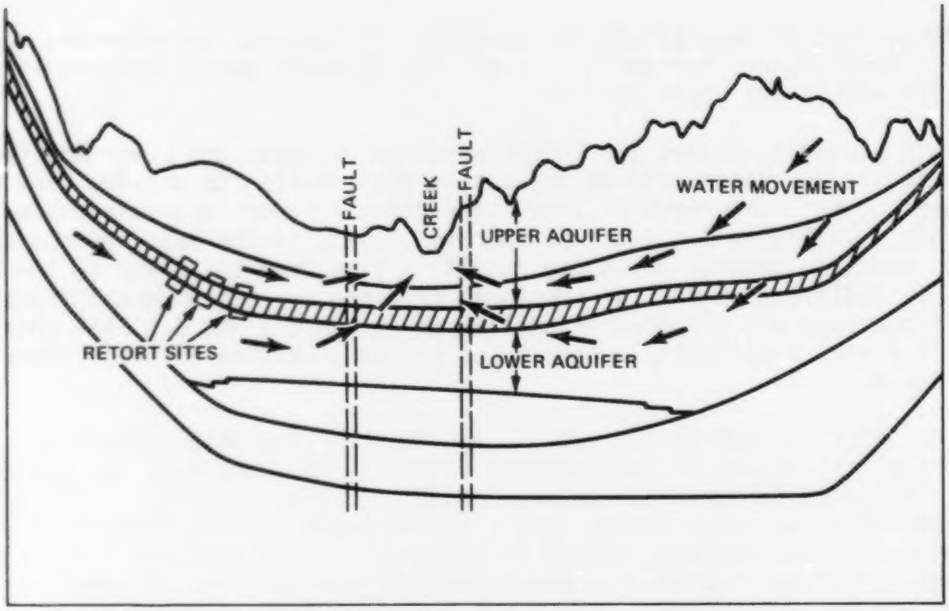
FAULT
CREEK
FAULT
WATER MOVEMENT
UPPER AQUIFER
RETORT SITES
LOWER AQUIFER

Figure A-1. Geohydrologic cross section of the Piceance Basin showing relationship of in-situ retorts to adjacent aquifers (Amy, 1978).

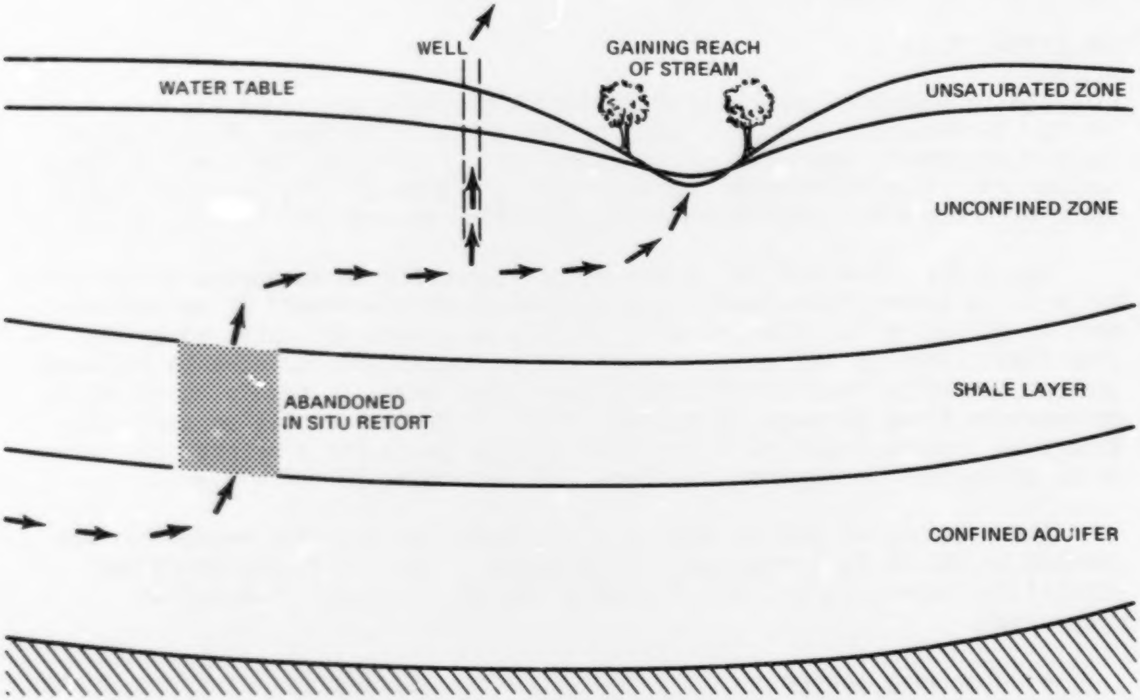
WELL
GAINING REACH OF STREAM
WATER TABLE
UNSATURATED ZONE
UNCONFINED ZONE
ABANDONED IN SITU RETORT
SHALE LAYER
CONFINED AQUIFER

Figure A-2. Schematic describing possible groundwater transport of leached contaminants.

phenomena, such as adsorption, ion exchange, filtration, and microbial degradation. Furthermore, contaminant levels may decrease due to dispersion and diffusion within the Upper Aquifer.

This scenario assumes the interconnection of Upper and Lower Aquifer zones via the abandoned retorts and a head distribution to provide flow from the Lower to the Upper Aquifer zone. The potential for interconnection is uncertain. On Tracts C-a and C-b, the head levels in the Upper and Lower Aquifer zones in general would not result in flow from the Lower to the Upper zone. In addition, it must be concluded from the preceding descriptions of the hydrogeology and groundwater quality of Tracts C-a and C-b that this scenario is a very simplistic expression of the complexities of the Piceance Creek Basin.

The actual direction and rate of groundwater flow after cessation of dewatering will depend on the response of the various aquifers and aquifer zones. Response is expected to vary between different aquifers. The early response cannot be predicted at this time and hence a likely long-term equilibrium condition (for some sites) is assumed for this analysis. The magnitude and character of potential water quality problems from MIS development will be greatly influenced by local stratigraphy, groundwater quality, local aquifer characteristics, and the relation of in-situ retorts to aquifers, wells, faults, springs, and other hydrogeologic features. In addition, the effects of operation of a number of MIS facilities in the Piceance Creek Basin have not been considered.

CONCEPTUAL MODEL 2

The following discussions of pollutant mobility are taken (1) from studies by Lawrence Berkeley Labs (LBL) on the potential effects of in-situ oil shale development, and (2) from hydrogeologic assessments for the Rio Blanco nuclear gas stimulation experiments. Both of these efforts included assessments of groundwater characteristics, including groundwater flow velocity.

LBL (1978) examined the transport of leachate from abandoned in-situ retorts using a one-dimensional, longitudinal dispersion model of solute transport in porous media. The validity of this model was not assessed by LBL. A step input function was used representing an instantaneous increase in leachate concentration from the retort to some level where it remains constant as groundwater flows through the system. This is probably a better approximation than a pulse input as it may take several years for a retort pore volume to be discharged to adjacent aquifers (LBL estimates 10 to 15 years).

Any attenuation due to sorption, ion exchange, or other mechanisms was assumed by LBL to be linear and instantaneous. LBL (1978) indicated that solubility, ion exchange, and adsorption may be important attenuation mechanisms.

- Solubility controls
  - Quantitative prediction of solubility/precipitation is not possible because equilibrium constants for participating

reactions in leachate-aquifer complex are not known

- Leachate will encounter ligands, such as oxides, hydroxides, carbonates, hydroxide-carbonate minerals
- Organic matter (as well as some inorganic constituents) present may diminish oxygen levels and enhance solubility of metals, such as iron and manganese
- Levels of calcium and magnesium are likely controlled by solubility of carbonates and hydroxides

- Adsorption
  - Presence of colloidal material will create sites for adsorption of organic and inorganic constituents
  - Adsorption is highly pH dependent and will likely control transport of zinc and chromium
- Ion exchange
  - This mechanism is probably of diminished importance due to the low clay content of the aquifer matrix; the exchange capacity of fractured oil shale, siltstone, sandstone is expected to be low
  - The exchange capacity of spent in-situ oil shale was not evaluated.

LBL used the following relationship to estimate equilibrium composition of leachate within a spent in-situ retort

$$\overline{C}_i = \frac{10M_i m + (C_g)_i V}{V} \qquad \text{(A-1)}$$

where $\overline{C}_i$ is the average concentration of the i^{th} constituent; M_i is the mass (in milligrams) of the i^{th} constituent per 100 grams spent shale (see Section 3); m is the mass of spent shale in a single retort (3.4×10^8 kilograms); $(C_g)_i$ is the concentration of the i^{th} constituent in groundwater in milligrams per liter; and V is the pore volume of a single retort (9×10^7 liters). This approach resulted in the estimates listed in Table A-1. The most limiting factor in making these estimates is the term M_i; however, the other terms in the above equation are also rough estimates.

The following parameters were used by LBL in their modeling study (from Weeks et al., 1974):

- Upper Aquifer
  - Transmissivity = 134 ft^2/day

TABLE A-1. ESTIMATED COMPOSITION OF LEACHATE WITHIN A SPENT IN-SITU RETORT LOCATED IN THE PICEANCE BASIN (from LBL, 1978)

		Retort located in Piceance Basin			
Constituent	Distilled water leachate composition (mg/100 g)	Quality of Lower Aquifer (mg/l)	Average concentration of leachate within retort if leached with Lower Aquifer water[a] (mg/l)	Quality of Upper Aquifer (mg/l)	Average concentration of leachate within retort if leached with Upper Aquifer water[a] (mg/l)
Al	0.095 - 2.8	0.18	3.8 - 110	0.14	3.7 - 110
B	0.075 - 0.14	1.3	4.1 - 6.6	0.67	3.5 - 6.0
Ca	3.6 - 210	18	2.7[b]	61	2.7[b]
Cl	5.5	32	240	17	220
CO_3	30 - 215	100	1,200 - 8,200	26	1,200 - 8,100
Cr	0.002 - 1.8	0.004	0.08 - 68	0.003	0.08 - 68
F	1.2 - 4.2	15	60 - 170	3.1	48 - 160
Fe	0.0004 - 0.042	3.4	3.4 - 5.0	5.4	5.4 - 7.0
HCO_3	22 - 40	1,000	1,900 - 2,500	620	1,500 - 2,100
K	0.76 - 18	1.4	30 - 680	1.1	30 - 680
Li	0.020 - 0.42	0.035	0.79 - 16	0.01	0.77 - 16
Mg	0.002 - 8.0	32	2.1[b]	58	2.1[b]
Na	8.8 - 235	510	840 - 9,400	280	610 - 9,200
NO_3	0.2 - 2.6	0.33	7.9 - 99	0.55	8.1 - 99
Pb	0.014 - 0.017	1.0	1.5 - 1.6	0.40	0.93 - 1.0
Si	25 - 88	4.8	550 - 3,300	12	960 - 3,300
SO_4	50 - 130	180	25[c]	360	25[c]
Zn	0.001 - 0.025	1.4	1.4 - 2.3	0.79	0.83 - 1.7
TDS	80 - 2,100	1,400	4,400 - 80,800	1,140	4,200 - 80,500
TOC	0.9 - 38	12	46 - 1,140	10	44 - 1,400

[a] Assumes the mass of spent shale in the retort is 3.4×10^8 grams and the volume of water contained by the retort is 9×10^7 liters. Computed using Equation A-1. For example, the lower B value shown in the second column is computed as:

$$\frac{(0.075)(3.4 \times 10^8) + (0.67)(9 \times 10^7)}{9 \times 10^7} = 4.1 \text{ mg/l}$$

[b] Based on solubility calculations for reactions presented in LBL (1978)

[c] Based on data presented by Jackson et al. (1975)

  - Storage coefficient = 0.001
  - Hydraulic gradient = 0.011
  - Thickness of saturated zone = 300 ft
  - Darcy velocity = 0.005 ft/day
  - Effective porosity = 0.1
  - Flow velocity = 0.05 ft/day

- Lower Aquifer
  - Transmissivity = 268 ft^2/day
  - Storage coefficient = 0.0001
  - Head = 25 feet above that of Upper Aquifer (static water level)
  - Hydraulic gradient = 0.011
  - Thickness of saturated zone = 600 ft
  - Darcy velocity = 0.005 ft/day
  - Effective porosity = 0.1
  - Flow velocity = 0.05 ft/day

- MIS retort
  - Potential maximum flow from Lower to Upper Aquifer = 1.1 x 10^6 gallons per day (assuming vertical permeability of 500 gallons per day per square foot and head difference of 25 feet)
  - Flow into and out of retort will be limited by lower permeability of aquifers (about 3.3 gallons per day per square foot); hence typical flow expected is about 3000 gallons per day)
  - Darcy velocity = 0.016 ft/day
  - Effective porosity = 0.2
  - Flow velocity = 0.08 ft/day.

Using this model, LBL estimated that travel times of leachate discharged to the Upper Aquifer would be about 300 years per mile (18 feet per year). The resultant impacts of a 100,000-barrel-per-day operation on surface water quality were estimated as follows:

Location	Average annual discharge (10^3 acre-feet)	Maximum TDS increase (mg/l)	Maximum TOC increase (mg/l)
Piceance Creek at White River	14.5	2,600 - 64,000	30 - 1,100
White River near Watson	532	80 - 1,900	1 - 30
Green River near Green River	4,427	10 - 230	0.1 - 4
Colorado River at Lee's Ferry	12,426	3 - 80	<0.01 - 1

Although simplistic analyses such as those described above provide some insight into the potential for groundwater quality impact, the nature and effect of the simplifying assumptions must be considered. For example, transmissivities of 134 and 268 ft^2/day were used in the model for the Upper and and Lower Aquifers, respectively. It should be noted that values of up to 1000 and 2000 ft^2/day, respectively, have been observed and that the aquifer test methods employed may be questioned (see Section 5). Also, most of the flow is through fracture sets of varying hydraulic character and strata of relatively high hydraulic conductivity have been observed on both sides of the Mahogany Zone. Thus, the flow rates into and out of the MIS retorts may be greater than the averaged levels used in the model and the potential for dilution in the Upper Aquifer zone may be diminished.

Two published studies related to the Rio Blanco nuclear gas stimulation experiment in the Piceance Basin are available: the environmental statement (U.S. Atomic Energy Commission, 1972) and a related follow-up study of possible groundwater transport (Knutson, 1973). Initial geophysical testing included the following:

- Dual induction resistivity
- Sidewall neutron porosity
- Bore hole compensated sonic
- Gamma ray
- Caliper logs
- Temperature log.

In addition, short-term jetting tests were conducted on Upper and Lower Aquifers:

Aquifer	Discharge rate (gpm)	Test length (min)	Drawdown (ft)	T (ft^2/day)	Water yielding interval (ft)
Upper	644	125	33	617	220
Lower	114	261	311	27	110

Hydraulic conductivity was thus estimated to be 2.8 and 0.3 ft^2/day in the Upper and Lower Aquifers, respectively (U.S. Atomic Energy Commission, 1972). Assuming an average gradient of 100 feet per mile and an effective porosity of 15 percent (approximately one-half the weighted average total porosity derived from the sidewall neutron porosity log), velocities were estimated as follows:

Aquifer	Representative velocity (ft per year)	With maximum gradient (ft per year)
Upper	130	285
Lower	12	25

A later assessment (Knutson, 1973) reevaluated estimates of fracture porosity and permeability yielded the following:

Aquifer	Thickness (ft)	Average porosity	Average permeability (darcy)
Upper	260	0.125	2.0
Lower	185	0.0198	0.05

Using these parameters and a gradient of 100 feet per mile yielded flow velocity estimates of 11.7 feet per day (4270 feet per year) in the Upper Aquifer and 0.256 feet per day in the Lower Aquifer. At this Upper Aquifer flow velocity, estimated travel time from the C-b boundary to Piceance Creek is 1.2 years. However, the actual time to discharge to Piceance Creek is unclear because of the uncertain location of the nearest aquifer discharge area to the surface.

CONCEPTUAL MODEL 3

Because of the as yet unknown operational conditions of in-situ oil shale retorting in Tract C-a, subsequent effects on groundwater quality are difficult to assess. It is recognized that inorganic, organic, and trace metal pollutants will be produced by the retorting. These will be released from the abandoned retorts into inflowing groundwater. As the retorts fill with water, the pollutants will go into solution and be transported by the moving groundwater.

Pollutants generated by the in-situ process are described in Section 3. The largest concentrations and the most mobile are the inorganic ions in solution in groundwater. Prime examples include sodium, bicarbonate, nitrate, and sulfate ions. These ions tend to remain in the solution, although they may be affected by precipitation (solubility controls) or biological activity. The chief mechanism for their reduction in concentration is dispersion--involving dilution with increasing volumes of groundwater as the constituents are transported downgradient. The effect is analogous to smoke decreasing in concentration with distance downwind. However, the effects of dispersion processes in groundwater are not as great or rapid as in the atmospheric analogy.

To provide a basis for evaluating the mobility of pollutants from an in-situ retort operation, a generic analysis will be undertaken based in part on hydrogeologic conditions existing in Tract C-a. A variety of conditions will be assumed in order to illustrate different pollutant movements. It is anticipated that these will be representative of most MIS operations in the Western United States.

Assumed Retort and Hydrogeological Conditions

Let the development plan for an oil shale tract consist of nine retort fields to be mined sequentially as indicated in Figure A-3. Each field will involve a square 4000 feet on a side, while the vertical thickness of the retorts will average 800 feet. Retorting will require 5 years to complete in each field, so that mining of the tract will terminate in Field 9 after 45 years.

Retorts will be mined, then rubblized, and finally burned to transform kerogen to oil. An abandoned retort will consist of a cavity with spent shale occupying the lower portion. Assuming the retort is in hydraulic contact with one or more aquifers, as it cools it will fill with groundwater. Examples of retort-aquifer geometries are sketched in Figure A-4. In Figure A-4a, a single aquifer overlies the abandoned retort, while in Figure A-4b the retort connects with Upper and Lower Aquifers.

The large void space (relative to surrounding rock mass) in an abandoned retort functions as a large-diameter well. The permeability within the retort can be regarded as effectively infinite (i.e., expected inflow rates will be small relative to maximum possible flow rate through retort). Thus, groundwater moves into, through, and from a retort with little flow resistance. Representative flow paths for groundwater are shown in Figure A-4 after the retort has filled with groundwater and steady-state flow conditions have been established. Note in Figure A-4a that groundwater enters and leaves the retort as a result of the ease of flow within the retort cavity. In Figure A-4b, the piezometric surface of the Lower Aquifer exceeds that of the Upper Aquifer; therefore groundwater flows vertically upward within the retort. This situation permits inter-aquifer transfer of groundwater.

An important point to note in both situations shown in Figure A-4 is that groundwater circulates freely within the retort. By so doing, it continuously

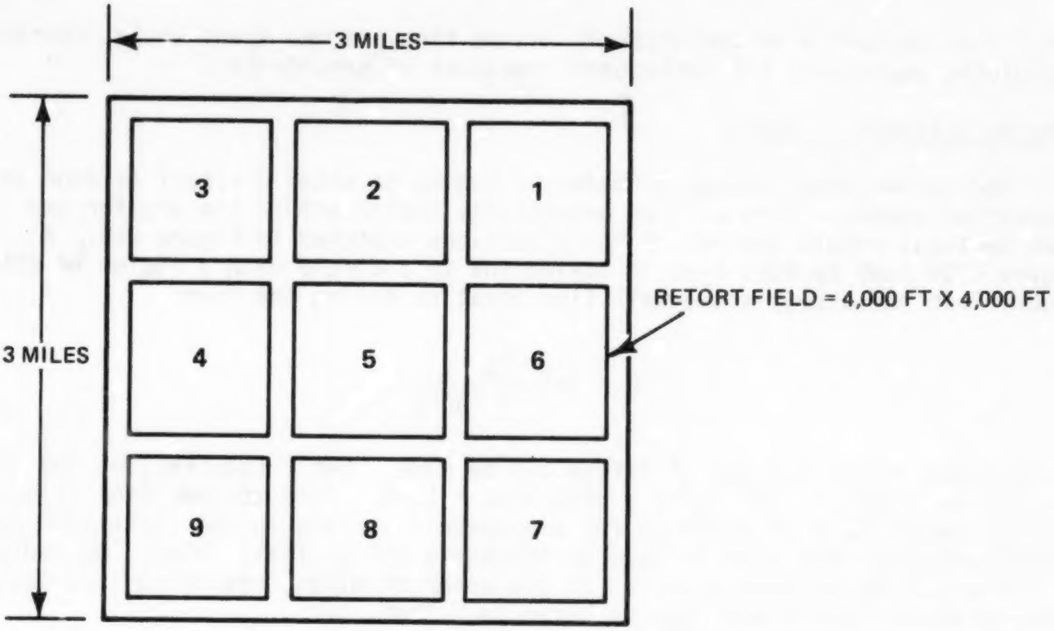
3 MILES
3 MILES
3
2
1
4
5
6
9
8
7
RETORT FIELD = 4,000 FT X 4,000 FT

Figure A-3. Hypothetical oil shale tract showing retort fields and sequence of development for Conceptual Model 3.

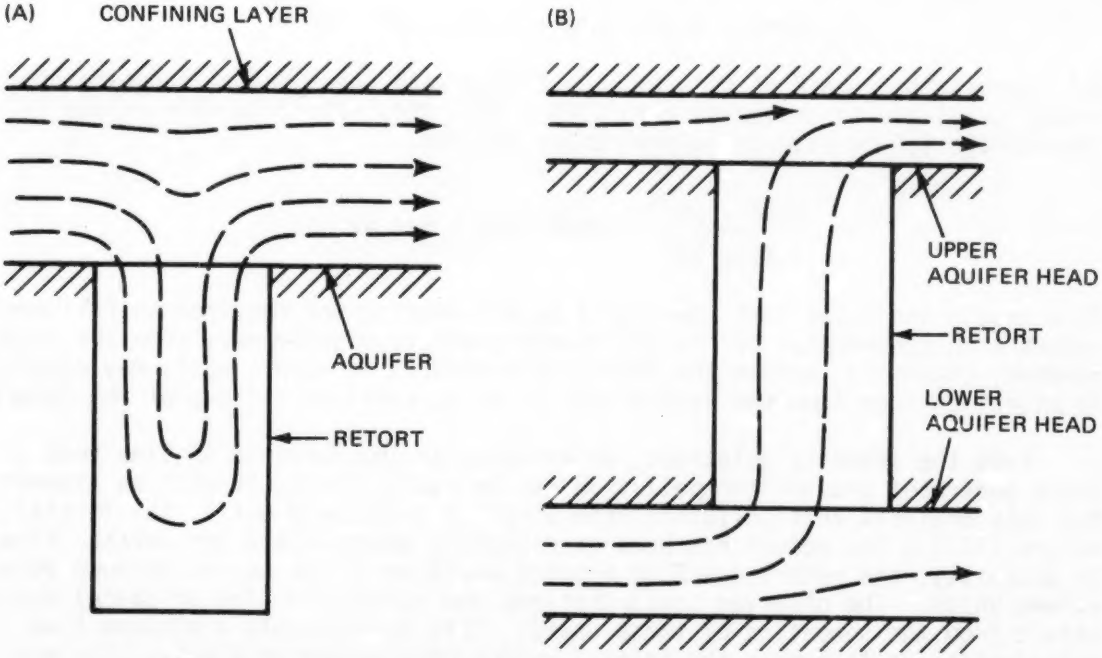
(A)
CONFINING LAYER
AQUIFER
RETORT
(B)
UPPER AQUIFER HEAD
RETORT
LOWER AQUIFER HEAD

Figure A-4. Retort-aquifer configurations and groundwater paths for Conceptual Model 3.

comes into contact with the minerals in the fine-grained spent shale, thereby dissolving pollutants for subsequent transport of groundwater.

Time to Saturate a Retort

For convenience, assume groundwater begins to enter a retort as soon as combustion ceases. Flow will be essentially radial within the aquifer and then vertical within the retort for conditions sketched in Figure A-5. A square 4000 feet by 4000 feet is equivalent to a circle with a radius of 2250 feet. From the steady-state well flow equation having the form:

$$Q = 2\pi T \frac{h_2 - h_1}{\ln r_2/r_2}$$

an estimate of the average of inflow can be made. Let T (aquifer) = 1000 ft^2/day, h_2-h_1 = 200 ft, and r_2/r_1 = 3250/2250 = 1.44. This assumes (for illustration here) 200-foot drawdown for piezometric surface in the first 1000 feet radial distance only with an aquifer thickness 200 of feet. Also, the radius of influence may be much greater (on the order of miles) resulting in a less steep gradient and slower time to saturate. Then

$$Q = 2\pi(1000)\,\frac{2000}{\ln 1.44} = 3.42 \times 10^6\ ft^3/day.$$

The gross volume of a retort is

$$4000 \times 4000 \times 800 = 1.28 \times 10^{10}\ ft^3$$

but approximately half of this will be filled with spent shale, reducing the volume available to groundwater to $0.64 \times 10^{10}\ ft^3$. Dividing this volume by the average inflow rate calculated above yields:

$$\frac{0.64 \times 10^{10}}{3.42 \times 10^6} = 1870 \text{ days} = 5.1 \text{ years.}$$

This result indicates that there will be a 5-year period required to fill each retort with groundwater before pollutants begin to migrate away from the site. However, channeling within the retort or fractures in retort walls may result in migration away from the retort zone prior to complete filling of the retort.

From the above calculations, an estimate of the duration of time that a tract generates groundwater pollution can be made. First, it will be assumed for this analysis that pollution from a retort lasts only until the initial volume filling the retort has been displaced by steady-state groundwater flow. In actuality, the retort leaching process would be a time series of such pore-volume units. The observed concentrations downstream (in time or space) would result from the summation of these units. This is certainly a minimum time calculation, as it treats the initial retort pore volume as a unit. The water entering and leaving a retort is assumed for this simplistic analysis to

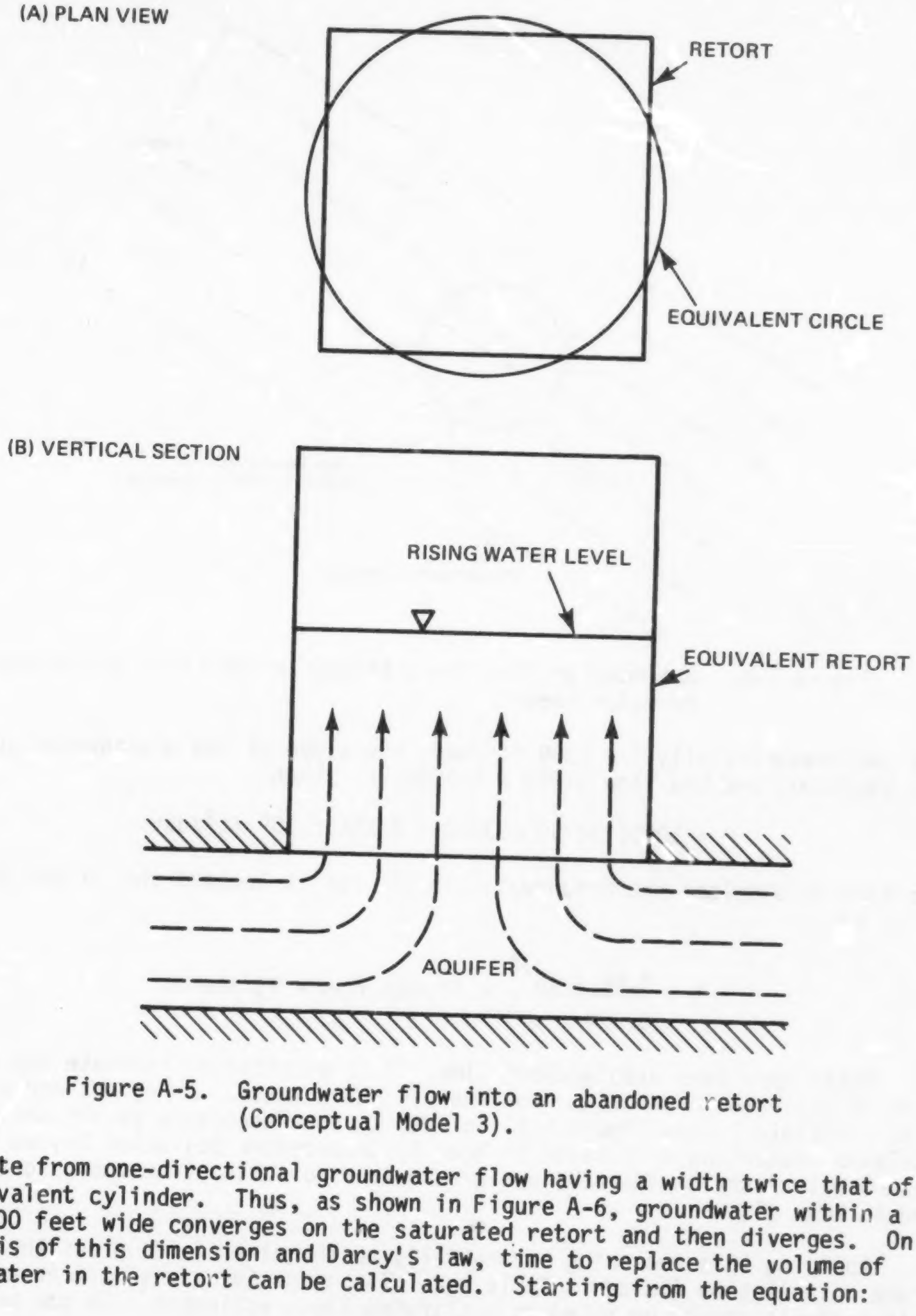
(A) PLAN VIEW
RETORT
EQUIVALENT CIRCLE
(B) VERTICAL SECTION
RISING WATER LEVEL
EQUIVALENT RETORT
AQUIFER

Figure A-5. Groundwater flow into an abandoned retort (Conceptual Model 3).

originate from one-directional groundwater flow having a width twice that of an equivalent cylinder. Thus, as shown in Figure A-6, groundwater within a band 9000 feet wide converges on the saturated retort and then diverges. On the basis of this dimension and Darcy's law, time to replace the volume of groundwater in the retort can be calculated. Starting from the equation:

$$Q = TiW$$

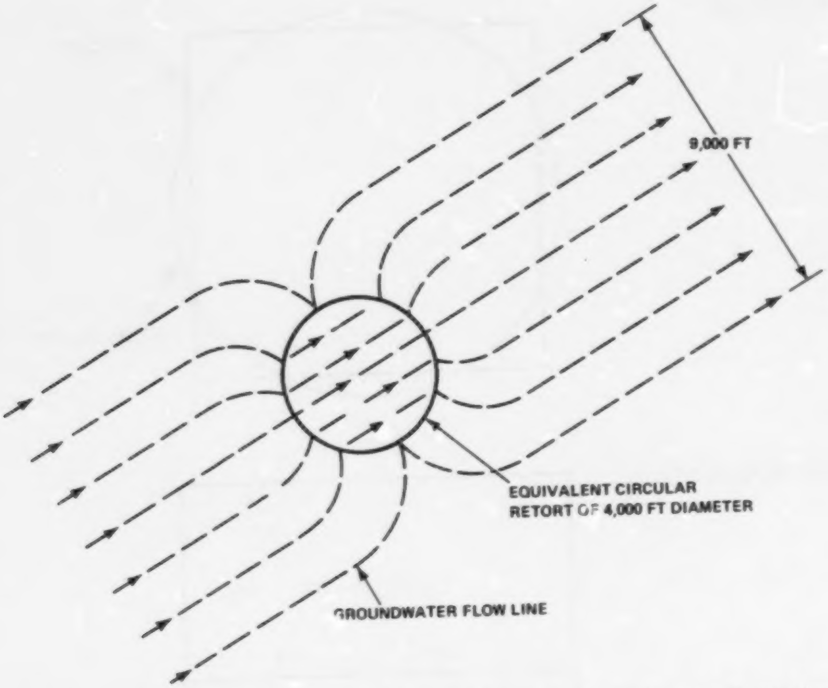

Figure A-6. Groundwater flow lines through a saturated equivalent circular retort.

let the transmissivity $T = 1000\ ft^2/day$, the slope of the groundwater surface $i = 130/5000$, and the flow width $W = 9000$ ft. Then

$$Q = 1000(130/5000)9000 = 0.234 \times 10^6\ ft^3/day.$$

The time to displace the groundwater in the retort becomes the volume divided by Q, or

$$T = \frac{2.64 \times 10^{10}}{0.234 \times 10^6} = 27{,}400 \text{ days} = 75 \text{ years.}$$

Based upon this displacement time, it is possible to indicate the duration of pollution production from the oil shale tract. If retort operations start in Field 1 (see Figure A-3) in Year 1, then according to the above analysis, retorting will cease in Year 5, groundwater pollution beyond the retort will start in Year 10, and groundwater pollution from the retort will end in Year 85.

Applying this reasoning sequentially to the nine fields gives the time frame of pollution listed in Table A-2. The simplifying assumptions used in this analysis should be noted as qualifying these estimates. It can be seen that the potential groundwater pollution from an oil shale tract can be a long-lasting phenomenon.

TABLE A-2. ESTIMATED DURATION OF GROUNDWATER POLLUTION PRODUCED BY AN OIL SHALE TRACT (RETORTING OPERATIONS START IN YEAR 1), CONCEPTUAL MODEL 3

Retort field	Year of first pollution production	Year of last pollution production
1	10	85
2	15	90
3	20	95
4	25	100
5	30	105
6	35	110
7	40	115
8	45	120
9	50	125

Migration of Pollutants in an Infinite Aquifer

An estimate of the movement of pollutants can be made assuming no attenuation of inorganic pollutants (except by dispersion) and flow in an infinite aquifer. The velocity of flow can be calculated from the Darcy equation in the form:

$$v = \frac{Ki}{\alpha}$$

where K is aquifer permeability, i is the gradient of the groundwater level, and α is aquifer porosity. Estimated values include: $K = T/b = (1000\ \text{ft}^2/\text{day})/200\ \text{ft} = 5\ \text{ft/day}$; $i = 130/5000$; and $\alpha = 0.1$. Substituting:

$$v = \frac{5(130/5000)}{0.1} = 1.3\ \text{ft/day} = 475\ \text{ft/yr} = 0.1\ \text{mi/yr}.$$

With this velocity and the durations of pollution given in Table A-2, the extent of pollution migration is given by the product of velocity times duration. The above flow analysis represents an idealized approximate analysis because it neglects inter-retort field flows. Treatment of this flow complexity is beyond the scope of this monitoring program design. However, it can be anticipated that this flow interference would tend to delay pollution migration.

It should be noted that this groundwater velocity calculation method yields correct estimates for a homogeneous aquifer. However, in an aquifer system with preferential zones of high permeability, the calculation would be in error, perhaps by several times. This factor is extremely difficult to quantify, particularly over large distances due to the heterogeneity of the fractured rock, solution cavity aquifer in the oil shale region. The potential for channels of rapid flow is greatly enhanced by this type of porosity.

Migration of Pollutants to a Stream

The previous analysis of pollution travel is physically somewhat unrealistic because rarely would groundwater travel extended distances without discharge to a surface stream, either as base flow or as a series of springs. With a velocity of 0.1 mi/yr and groundwater discharge to a stream 5 miles from the tract, the travel time underground would amount to 5.6 years. Adding 10 years from the start of production means that surface water pollution would begin about Year 15.6 and continue for some 75 years (see preceding analysis).

Pollutant Concentration

Because pollution may originate from retort fields at different times, the total pollution mass varies as a function of time. The time distribution of pollution can be derived from the data in Table A-2 assuming that the concentration emanating from a given retort field remains constant with time. Actually, this assumption appears reasonable in that mixing within the retort may tend to produce a uniform concentration which is then replaced with a subsequent volume of water without pollution. Thus, each retort field may be illustrated as producing a step-funtion of pollution for a 75-year period (see preceding analysis). Combining these in the sequence given by Table A-2 yields the pollution concentation curves shown in Figure A-7. Note that a pyramid-shaped curve is formed with a maximum concentration persisting for 35 years.

Another, and perhaps more realistic, model of these processes is to visualize considerable mixing as polluted water within the retort is displaced from below. Density currents may develop as the highly polluted water is displaced upward by less dense unpolluted water. In addition, rather than water being displaced uniformly across the entire bottom of the retort, water may enter the upgradient side of the retort and then channel directly upward because of its lower density. These effects, plus diffusion, would act to decrease the concentration of pollutants flowing from the retort but would also prolong the length of time of leaching from the retort.

Attenuation of Pollutants

The primary mechanism for attenuation of inorganic pollutants underground is dispersion. By mixing with ever-increasing volumes of groundwater, a plume of potential pollutants downgradient from an oil shale tract expands in volume and consequently decreases in concentration. For a given water quality criterion, there is a maximum recommended limit; an example would be SO_4 = 250 mg/l for potable water supplies. If the initial SO_4 concentration of groundwater leaving the retort exceeds this value, then at some distance from the retort the quality improves to meet this criterion.

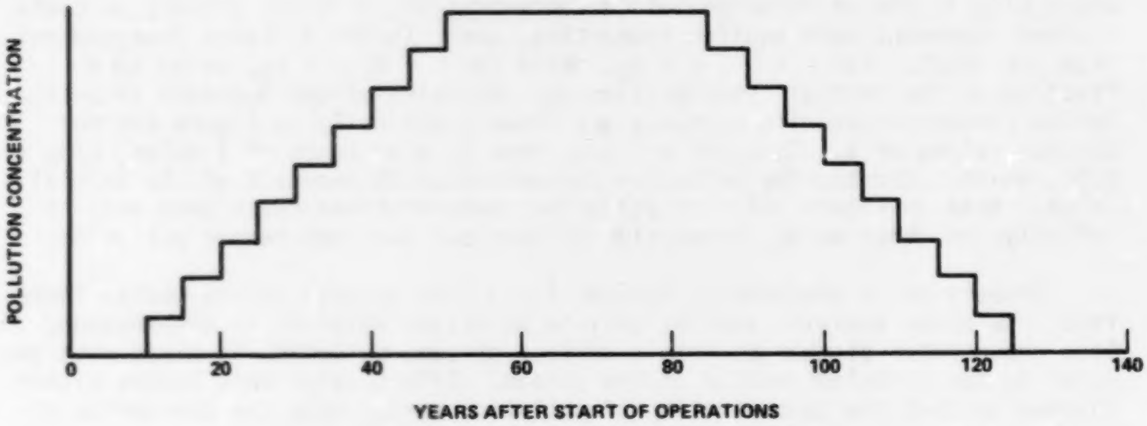

Figure A-7. Groundwater pollution concentration as a function of time from oil shale tract, using Conceptual Model 3.

Determination of the distance from a tract to where the water is of satisfactory quality depends upon three factors:

1. Initial constituent concentration leaving the tract
2. Water quality criterion for a specified water use
3. Physical properties of the aquifer--grain size, grain-size distribution, porosity, specific surface, gradient, flow velocity, flow patterns, etc.

The influence of these factors on the resulting concentration of individual chemical constituents is expected to be quite variable. Concentrations will also be affected by physico-chemical processses, such as precipitation and perhaps biological activity. Because of data limitations, it is not possible to describe quantitatively or precisely the rate of decrease of pollution concentration by dispersion for aquifers associated with oil shale tracts in the Western United States. This can only be accomplished based upon field measurements over a period of several years. Also, the dispersion rate for each aquifer is undoubtedly different. Models can, however, be useful to consider general cases and provide some insight into the potential effects on groundwater quality.

The only scenario that can be stated with certainty is that for a homogeneous and isotropic aquifer, dispersion produces an exponential decrease in concentration with distance. This is for a unit impulse input and ignoring mass transport (Lagrangian view of dispersion). This can be expressed as:

$$c/c_0 = e^{-aL}$$

where c/c_0 is the relative pollution concentration, a is the dispersion coefficient dependent upon aquifer properties, and L is the distance downgradient from the tract. For $L = 0$, $c = c_0$; while for $L > 0$, $c < c_0$, being some fraction of the initial concentration c_0. Examples of the decrease in pollution concentration with distance are shown graphically in Figure A-8 for various values of a. Thus, if $a = 0.8$, then at a distance of 3 miles, $c/c_0 = 0.50$, which indicates the pollution concentration is one-half of its initial value. Note in Figure A-8 that pollution concentrations reach zero only at infinity; in other words, dispersion dilutes but does not remove pollution.

Dispersion is produced by laminar fluid flow through porous media. Therefore, the above analysis applies only to pollution while it is underground. Once groundwater discharges into a surface stream, pollution is mixed with the water by the turbulent motion of the stream. Effectively, this occurs within minutes so that the concentration of pollution varies with the streamflow dilution. Streams near Tract C-a are small, hence pollution concentrations would be relatively large. But as the water flows to the White River, then to the Green River, and finally to the Colorado River, streamflow quantities

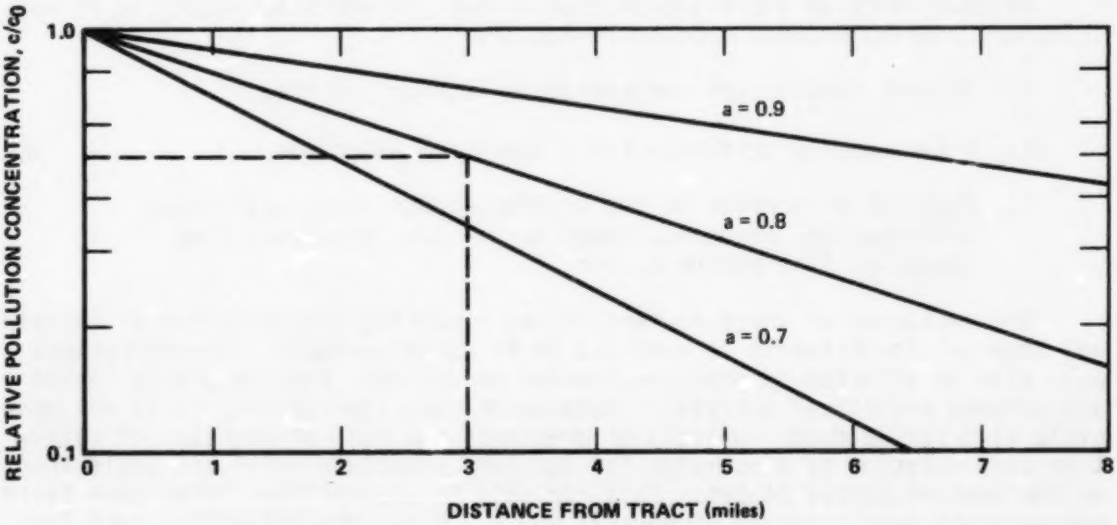

Figure A-8. Relative pollution concentration as a function of distance from an oil shale tract and of rate of dispersion (a is the dispersion coefficient).

increase, causing pollution concentrations to decrease. Similarly, because local streams have flows which vary seasonally, it can be expected that pollution concentrations will be least during the spring snowmelt season and largest during the low-flow season in late fall and winter.

REFERENCES

Amy, G.L., "Contamination of Groundwater by Organic Pollutants Leached from In Situ Spent Shale," Ph.D. dissertation, University of California, Berkeley, California, 1978.

Jackson, L.P., R.E. Poulson, T.J. Spedding, T.E. Phillips, and H.B. Jensen, "Characteristics and Possible Roles of Various Waters Significant to In Situ Oil Shale Processing," Quarterly of Colorado School of Mines, Vol. 70, 1975.

Knutson, C.F., Project Rio Blanco: Evaluation of Possible Radioactivity Transport in Groundwater, CER Geonuclear Corporation, Las Vegas, Nevada, 1973.

Lawrence Berkeley Labs (LBL), "Diffuse Source Effects on In Situ Oil Shale Development on Water Quality", draft report, 1978.

U.S. Atomic Energy Commission, Environmental Statement: Rio Blanco Gas Stimulation Project, Rio Blanco County, Colorado, April 1972.

Weeks, J.B., G.H. Leavesley, F.A. Welder, and G.J. Saulnier, Jr., Simulated Effects of Oil Shale Development on the Hydrology of Piceance Basin, Colorado, U.S. Geological Survey Professional Paper 908, 1974.